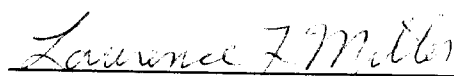
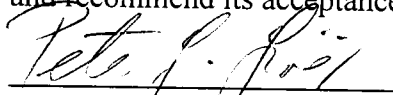


To the graduate Council:

I am submitting herewith a thesis written by Mark McHugh entitled "Radioassay of a Portion of the Main Radioactive Ventilation Header at the Radiochemical Development Facility Using In Situ Gamma Spectrometry Methods for Intact Fluid Systems." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.


Laurence Miller, Major Professor

We have read this thesis
and recommend its acceptance:




Accepted for the Council:


Associate Vice Chancellor and
Dean of The Graduate School

**Radioassay of a Portion of the Main Radioactive Ventilation Header
at the Radiochemical Development Facility
Using In Situ Gamma Spectrometry Methods for Intact Fluid Systems**

**A Thesis Presented for the
Master of Science Degree
The University of Tennessee, Knoxville**

Mark McHugh

December 1995

ABSTRACT

There exists a need for a method to radioassay components and fluid systems internally contaminated with radioactive material. Often operating constraints require these analyses to be performed without system penetration. The results of an accurate analysis of this type could be used for radiological planning and waste generation estimates. Gamma spectrometry methods are a valid choice, but have a large associated uncertainty due to unknown source distribution, shielding composition, and background radiation contribution.

The most common approach to the problem is to survey the component with a field survey meter and, given process knowledge of the isotope of concern, convert the exposure rate to an activity using a thumbrule. Some use of portable gamma spectrometry equipment has been made in this application, but the assumptions made to compensate for shielding and correct for unrepresentative efficiency calibration involve large margins of uncertainty. More often than not, the uncertainty in any of these methods is not well defined, even though it could approach several orders of magnitude.

A procedure was developed to use portable gamma spectrometry equipment to characterize the type and amount of radioactivity in an intact fluid system without system penetration. The background radiation contribution was eliminated using partial

shielding. The source and shielding distribution effects on the efficiency calibration were corrected by comparing fluence rate ratios to detector efficiency. This efficiency correction factor was based on fluence rates generated by both a point-kernel shielding software application and a Monte Carlo simulation software template run out of a spreadsheet application. The accuracy of the analysis was then measured by performing an uncertainty analysis on the entire process using numerical and analytical propagation of error techniques.

The entire portion of the header analyzed was determined to contain $872 \text{ Mbq} \pm 40 \%$ of ^{137}Cs ($^{137\text{m}}\text{Ba}$). The header was analyzed piece-wise, with an associated activity and uncertainty for each of the fifteen segments analyzed. The overall analysis uncertainty was based on the activity estimate and uncertainty analysis developed from the Monte Carlo simulation software template, which was found to be the more applicable software for this procedure.

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ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ADC	Analogue to Digital Converter
ANSI	American National Standards Institute
App.	Approximation
Bq	Becquerel — one disintegration per second of activity
Cal.	Calibration
^{137}Cs ($^{137\text{m}}\text{Ba}$)	Cesium-137 isotope in secular equilibrium with its short-lived meta-stable daughter, Barium-137m
cps	counts per second
D&D	Decontamination and Decommissioning
eV	electron Volt — a unit of energy
FWHM	Full Width at Half of the Maximum height
HEPA	High Efficiency Particulate Air
HP	Health Physics
HPGe	High Purity Germanium
hr	hour
^{40}K	Potassium-40 — naturally occurring isotope
LHS	Latin Hypercube Sampling
MCA	Multi-Channel Analyzer

MRV	Main Radioactive Ventilation
NIST	National Institute of Standards and Technology
ORNL	Oak Ridge National Laboratory
Pb	Lead
R	Roentgen — a unit of exposure equal to that amount of photons required to deposit one electrostatic unit of charge in one cubic centimeter of dry air at standard temperature and pressure
RDF	Radiochemical Development Facility

1. INTRODUCTION

A general method can be developed and evaluated to use gamma spectrometry equipment to characterize the isotopic contents of nuclear facility system components, in place and without breaching system integrity, even in fields of significant background radiation.

A system of methods was developed to perform gamma spectrometry on system components while in place. The results of this evaluation of system internal contamination, sometimes referred to as "hold-up counting", can be used for practical purposes such as nuclear criticality safety analysis (for fissile isotopes), maintenance or Decontamination and Decommissioning (D&D) planning. This planning can be applied in predicting necessary radiological safety requirements and estimating radioactive waste disposal needs.

The primary difficulties for spectrometry under these conditions are: (1) unknown source geometry and distribution; (2) unknown quantities and distribution of shielding materials; and (3) background radiation. None of these are a consideration when performing spectrometry under ordinary conditions (such as counting a known quantity of a sample in a given geometry, at a given distance, in a shielded laboratory setting). Due to these difficulties, each of the methods developed to perform "hold-up" spectrometry is an approximation with an associated uncertainty. These uncertainties

can be evaluated using uncertainty analysis principles and minimized by folding these principles into each stage of the development process.

The specific setting used to develop these methods was the west main radioactive ventilation header of the Radiochemical Development Facility (RDF-Bldg. 3019) at Oak Ridge National Laboratory (ORNL). The header is a typical contaminated fluid system with low points, instrumentation penetrations, valves, and other common hold-up points (Figure 1-1). It exhausts ambient room and hot cell ventilation for the hot cell area (Bldg. 3019B). The hot cells are responsible for both the radioactive contamination in the fluid system and the background radiation field which interferes with spectrometry measurement. Process knowledge and documented laboratory spectrometry analyses of filter media samples, from the associated system HEPA filters located at the down stream end of the header predetermined the primary nuclide of concern for this portion of the header to be ^{137}Cs ($^{137\text{m}}\text{Ba}$).

The specific instrumentation for this process was a portable High Purity Germanium (HPGe) detector with a 15% relative efficiency crystal and a Multi-Channel Analyzer (MCA) with a 16,384 channel Analogue-to-Digital Converter (ADC). The other instrumentation for this process was a simple field survey meter, an ionization chamber exposure-rate meter (Bicron RSO-5) to perform ducting and component scans and gradient field surveys.

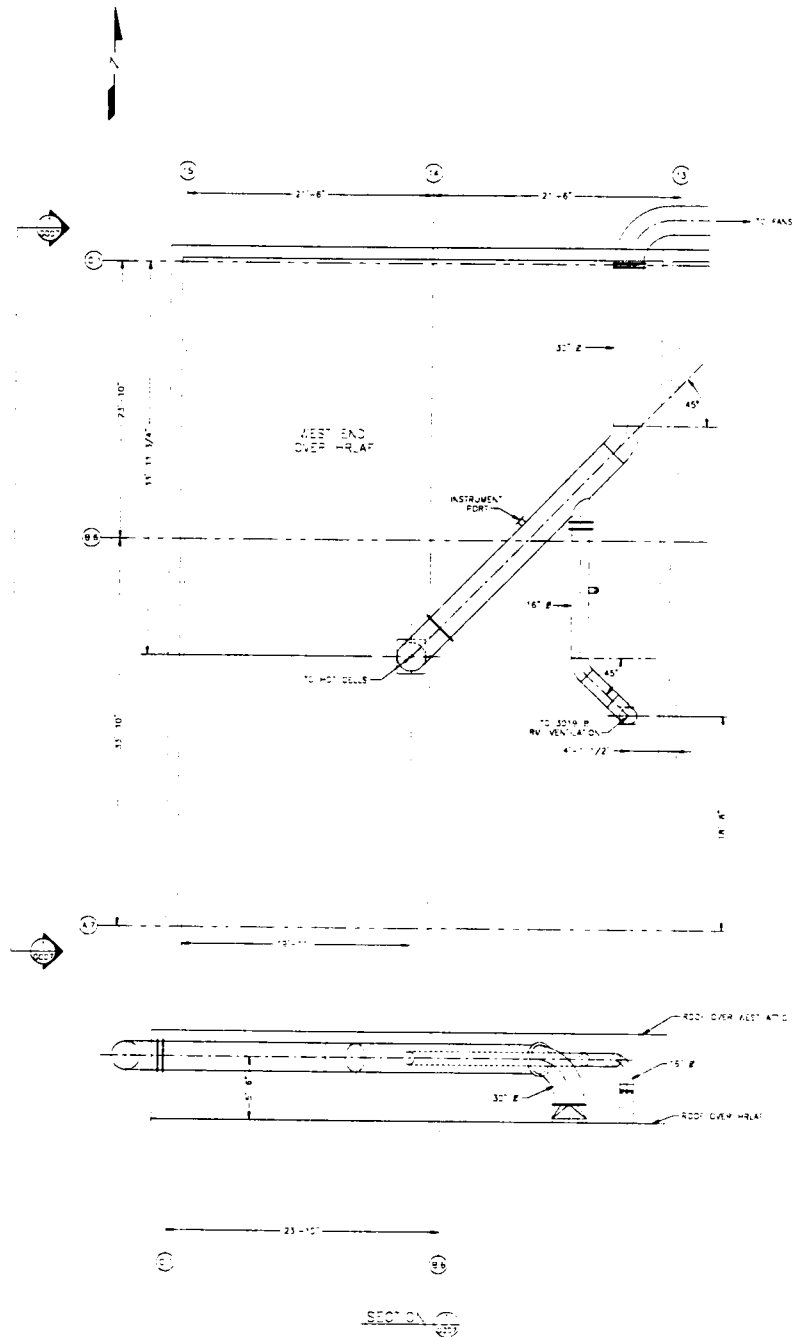


Figure 1-1 — Hot Cell Ventilation for Building 3019B on the RDF West Roof.

The general method is a four step process: (1) survey for source distributions; (2) perform experimental measurements; (3) perform computational analyses; and (4) evaluate through uncertainty analysis. (1) First, perform surveys with the field instrument to determine subject and background source locations and distributions, and background radiation gradients. Sensitivity analyses are performed to determine optimal counting positions. From this information, appropriate shielding and counting positions (subject and background) are established. (2) Once the subject and background counting positions are determined, then multiple counting positions are determined and counts are performed using spectrometry equipment. (3) Computer software packages, as well as field instrument survey data, are used to determine geometric efficiency factors for each counting position. These geometric efficiency factors along with a point source efficiency calibration for that energy provide the efficiency calibration needed for quantification. (4) An uncertainty analysis is performed on plausible sources of error and significantly sensitive parameters. An accurate approximation of system isotopic content with a verified confidence factor is the result of this process.

Each of the above steps one through four will be explained in detail in the following sections two through five respectively. Examples of the software computations and reports used for sections three through five are displayed in appendices A through C respectively. Sections two and three primarily address gathering data and qualitative

analysis of that data. In sections four and five the equations are developed to analyze this data quantitatively, and the relative accuracy of the quantitative estimate.

2. SURVEY METHOD

The gradient field survey method is presented to identify the subject and background source distributions, and evaluate the most effective counting positions and placement of shielding for the probe during in-place component characterization applications. The radiation gradients are established through the gradient field survey and complimented by an on-contact system scan of the potential source systems present. These gradients are evaluated and the major sources contributing to the field are identified.

Please note that if the isotopic nature of any of these sources is unknown, then they must be verified through a spectroscopy analysis. This is particularly important when dealing with sources of differing nuclides with vastly different gamma yields or energies. This is because the radiation field due to a high yield or high photon energy source can easily hide the distribution of a high activity but low yield or low photon energy source. This problem was addressed, and the activity was verified by preliminary gamma spectroscopy analysis to be ^{137}Cs ($^{137\text{m}}\text{Ba}$) for both the source to be characterized and the background

source. Therefore for this application, this method can be used as presented with no other complications.

The vector field characterized by the survey is used to project the radiation vector from the applicable major contributing sources to the desired counting positions. From this, the background spectrum contribution can be roughly estimated for each of the counting position. This allows background effects to be minimized through partial shielding and the remaining portion to be subtracted from each position's counts, if necessary.

2.1 Survey Procedure

The gradient survey and system scans were performed using the Bicron RSO-5 commonly used at ORNL by Health Physics (HP) personnel for radiation surveys. An HP field instrument was chosen over using the actual portable gamma spectrometry equipment because of the obvious ease of use and time efficiency. The 561 counting positions in the established grid and 72' of ventilation ducting scanned would not be a desirable application for heavy gamma spectrometry equipment. The field instrument was calibrated by ORNL HP instrument calibration personnel in accordance with ANSI N323-1978 (American National Standard: Radiation Protection Instrument Test and Calibration) and was in calibration at the time of use.

To begin, the area containing the system to be characterized was measured and a three-foot by three-foot grid was established using temporary markers (Figure 2-1). The gradient survey was conducted using a six-foot pole marked at three feet. A small level was attached to minimize inaccuracies in survey points. Measurements were made at each grid location at roof level, the three-foot mark (three feet above the roof), and the top of the pole (six feet above the roof). The center of the probe was consistently placed at each counting position and the attitude of the probe was maintained in a consistent direction.

The ventilation system was surveyed, on contact (scanned), over all accessible surfaces. Although top, bottom and sides were scanned, the radiation levels (above the background gradient) were up to an order of magnitude higher along the bottom at centerline. These highest levels were recorded at approximately one-foot intervals. Any remarkable levels on other portions of the system were also recorded.

2.2 Sources Identified

The gradient survey (see Tables 2-1, 2-2, and 2-3) identified the approximate location of the two major sources of radiation in the area (Figure 2-2). The hot cells beneath the roof in 3019B were, as suspected, a large area high activity source field originating at roof level (The darkly shaded area in Figure 2-2 indicates on contact readings with the roof in excess of four mR/hr.).

Example of
Grid Block
for Ducting
Scan Points
a, b, and c.

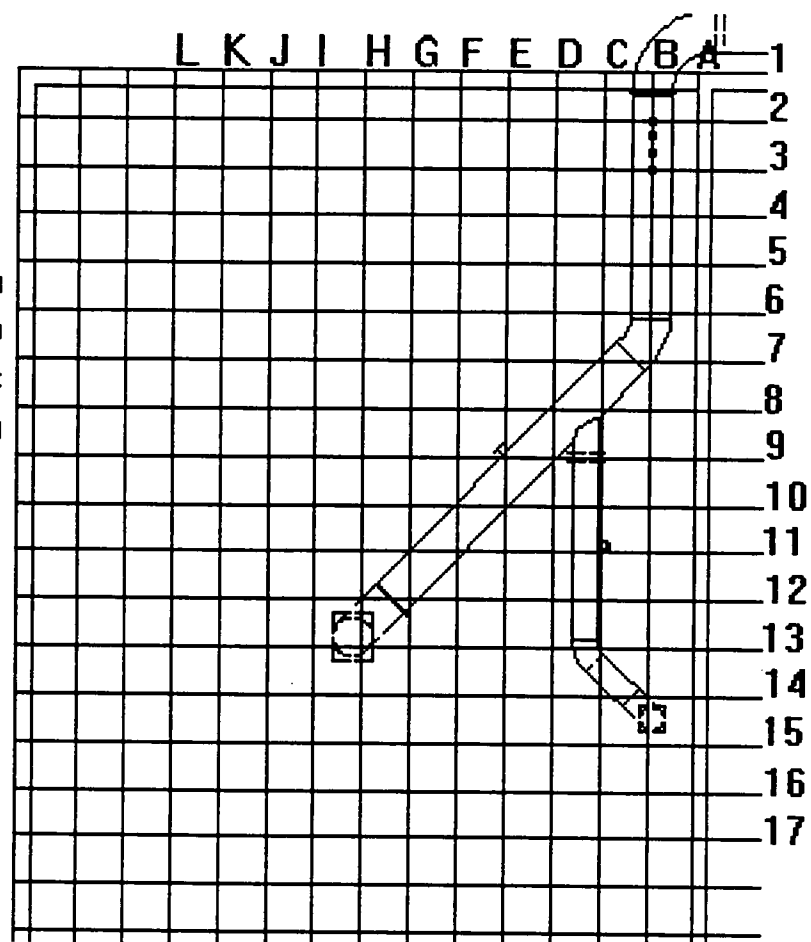
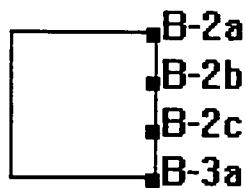


Figure 2-1 — Layout of the 3' by 3' Grid on the RDF West Roof. Grid survey locations are at grid line intersections. The example in the upper left corner corresponds to the grid points shown on the ventilation duct for the on-contact system survey.

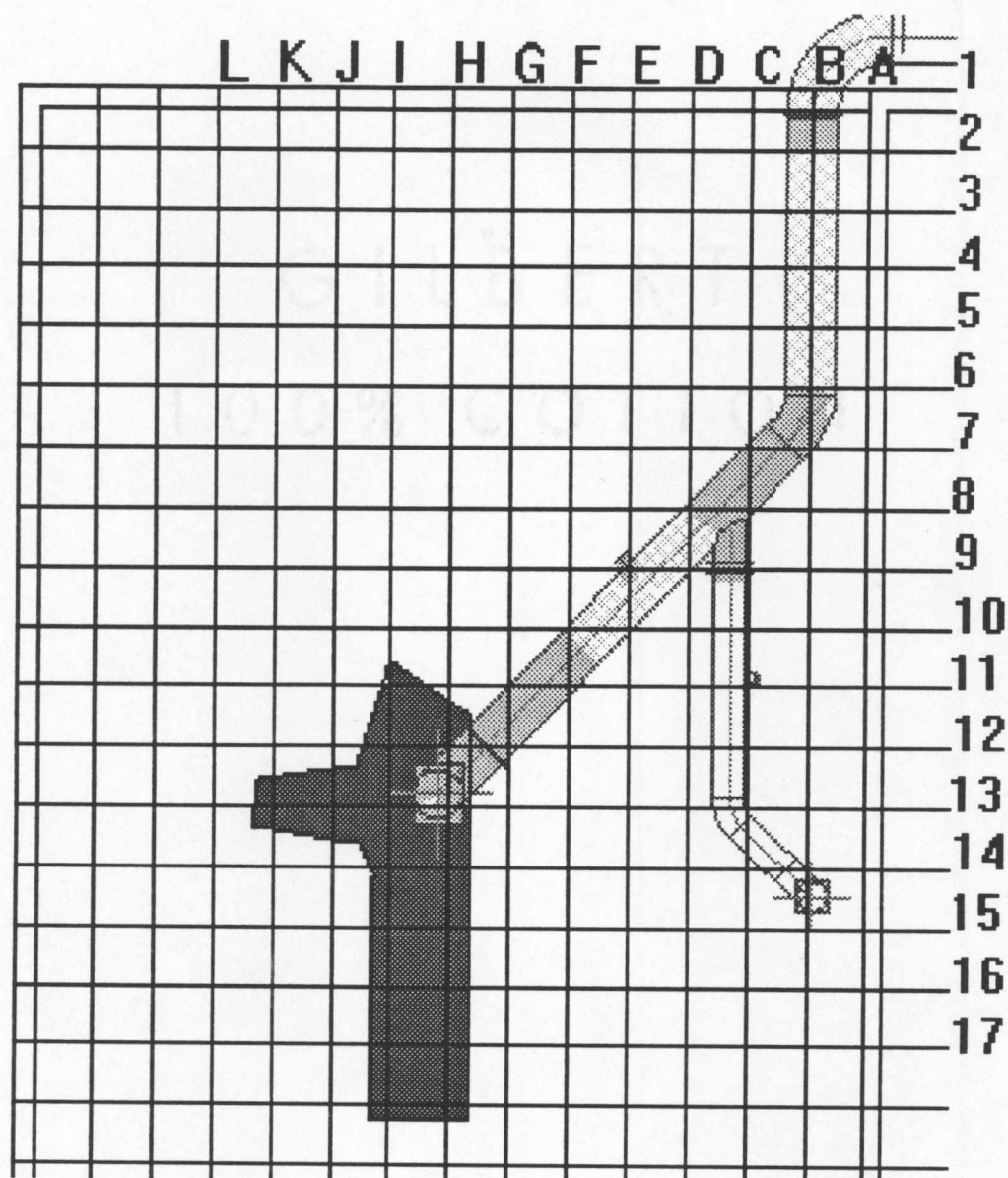


Figure 2-2 — The Primary Background Field Roof Penetration Area. Darkly shaded area is greater than four mR/hr on contact with the roof. The darkness of the shading on the ventilation ducting reflects radiation levels — darker is higher. The grid lines shown are three feet apart.

Table 2-1 — Gradient Field Exposure Rate at Roof Level.

L	K	J	I	H	G	F	E	D	C	B	A	
<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	.1	.2	.2	.2	1
<.1	<.1	.1	.1	.1	<.1	<.1	.1	.1	.2	.2	.2	2
.1	.2	.2	.4	.4	.1	.1	.2	.2	.2	.3	.3	3
.2	.3	.5	.9	.9	.2	.2	.2	.3	.3	.3	.3	4
.3	.6	1.0	1.5	1.6	.3	.2	.2	.2	.3	.4	.3	5
.4	.8	1.1	1.8	2.0	.4	.4	.3	.4	.4	.4	.3	6
.6	1.2	1.5	2.1	2.4	.5	.5	.4	.5	.4	.4	.3	7
.7	1.4	1.8	2.7	3.1	.6	.6	.5	.6	.5	.3	.3	8
.6	1.2	1.4	2.2	1.4	.6	.5	.5	.5	.5	.4	.3	9
1.0	2.0	2.2	3.2	3.0	.7	.6	.5	.5	.4	.3	.2	10
1.3	2.4	3.0	4.0	3.6	.8	.6	.5	.4	.3	.2	.2	11
1.7	3.5	3.2	4.0	4.8	1.0	.7	.4	.3	.3	.2	.2	12
1.8	4.5	5.0	8.0	X	1.4	1.0	.5	.3	.2	.2	.2	13
2.1	3.3	3.6	7.0	7.0	.9	1.0	.5	.3	.2	.1	.1	14
1.2	2.3	2.2	7.0	7.0	.9	1.0	.6	.3	.2	.1	.1	15
1.2	1.6	1.6	5.0	6.0	.7	.9	.6	.2	.2	.1	.1	16
1.3	.9	X	5.0	8.0	.6	.9	.3	.2	.2	.1	<.1	17

See Figure 2-1 for grid point locations. Surveys were performed with a Bicorn RSO-5 ionization chamber exposure rate meter. Exposure rates are listed in mR/hr. An "X" denotes that no measurement could be taken at that point due to an obstruction.

Table 2-2 — Gradient Field Exposure Rate at 3' above Roof Level.

L	K	J	I	H	G	F	E	D	C	B	A	
.1	.1	.1	.2	.2	.1	.2	.2	.3	.4	.6	.7	1
.2	.3	.3	.3	.3	.2	.2	.3	.3	.4	.6	.5	2
.2	.2	.3	.5	.5	.3	.2	.3	.3	.5	.5	.4	3
.3	.5	.6	.8	.7	.5	.4	.3	.4	.5	.5	.5	4
.5	.7	1.0	1.1	1.1	.5	.4	.3	.4	.5	.6	.5	5
.7	1.0	1.2	1.3	1.6	.7	.6	.5	.5	.6	.6	.5	6
.7	1.1	1.5	1.6	1.7	1.0	.7	.8	1.0	1.0	1.3	.6	7
1.0	1.3	1.7	1.9	1.9	1.0	.8	1.0	.9	1.3	1.0	.6	8
1.1	1.4	2.0	2.2	2.1	1.2	1.0	.9	.8	.9	.7	.5	9
1.3	1.8	2.6	2.8	2.8	1.7	1.5	1.4	1.0	.9	.6	.5	10
1.6	2.2	3.1	3.2	3.6	2.4	1.8	1.2	.9	.6	.5	.4	11
2.0	2.8	3.6	4.2	X	2.8	1.7	1.0	.8	.5	.5	.3	12
2.1	3.0	4.1	4.4	X	2.7	1.4	.9	.6	.5	.4	.3	13
2.0	2.7	4.0	4.0	4.8	2.5	1.2	.9	.7	.4	.4	.3	14
1.6	2.1	3.5	4.3	4.8	2.3	1.2	.9	.7	.4	.3	.3	15
1.5	1.8	3.9	4.2	4.5	2.2	1.1	.9	.6	.4	.3	.3	16
1.5	1.9	2.2	3.0	4.3	1.4	1.0	.8	.6	.4	.3	.2	17

See Figure 2-1 for grid point locations. Surveys were performed with a Bicron RSO-5 ionization chamber exposure rate meter. Exposure rates are listed in mR/hr. An "X" denotes that no measurement could be taken at that point due to an obstruction.

Table 2-3 — Gradient Field Exposure Rate at 6' above Roof Level.

L	K	J	I	H	G	F	E	D	C	B	A	
.1	.1	.2	.2	.2	.2	.2	.2	.3	.5	X	1.4	1
.2	.3	.3	.4	.4	.3	.3	.4	.4	.6	X	1.0	2
.2	.2	.3	.4	.5	.4	.3	.3	.4	.5	X	1.1	3
.3	.4	.5	.6	.6	.5	.4	.4	.4	.6	X	.9	4
.4	.6	.6	.7	.8	.5	.4	.4	.5	.6	X	.9	5
.6	.8	.9	.9	1.0	.8	.6	.6	.5	.8	X	1.1	6
.8	.9	1.0	1.0	1.1	.9	.8	.7	1.1	4.1	X	.9	7
.9	1.2	1.2	1.2	1.5	1.1	.9	1.1	2.7	X	1.4	.6	8
1.0	1.2	1.5	1.6	1.5	1.3	1.2	1.4	X	X	.7	.5	9
1.2	1.6	1.8	1.8	2.0	1.9	2.5	X	1.4	X	.6	.5	10
1.2	1.8	2.1	2.0	2.5	3.0	X	1.5	1.0	X	.5	.4	11
1.4	2.0	2.2	2.2	3.0	4.8	2.2	1.2	.8	X	.4	.3	12
1.7	2.1	2.3	2.1	2.2	2.4	1.6	1.1	.8	X	.4	.3	13
1.5	2.0	2.4	2.2	2.9	2.2	1.3	1.0	.6	.5	X	.3	14
1.6	2.0	2.1	2.0	2.8	2.2	1.2	.9	.7	.6	.4	.3	15
1.3	1.8	2.2	2.0	2.3	2.2	1.1	.8	.7	.5	.4	.3	16
1.5	2.2	2.5	2.5	2.6	1.4	1.0	.7	.6	.4	.3	.2	17

See Figure 2-1 for grid point locations. Surveys were performed with a Bicon RSO-5 ionization chamber exposure rate meter. Exposure rates are listed in mR/hr. An "X" denotes that no measurement could be taken at that point due to an obstruction.

The radiation field due to this source behaves similarly to a plane source with a very slow flux divergence as distance is gained between the field penetration of the roof and points of interest in the gradient field. The resultant field due to this source is difficult to model however, because the actual source is well below the roof's surface and the hot cell design shielding create severe inconsistencies in the field (see Figure 2-2 and Table 2-1 — the radiation levels at roof level on row "G", 3 feet from the high exposure plane, average less than one mR/hr, though row "H", six feet from the high exposure plane, average one mR/hr.)

The second major source of radiation determined by the gradient field survey and verified by the ducting scan (see Table 2-4) is the hot cell ventilation ducting. This includes the smaller room ventilation duct downstream of the associated isolation valve (see Figure 2-2 at grid point C-9). This activity is the subject to be characterized, but since the spectrometry procedure developed will characterize the system piece-wise, the portions not being characterized during a given count will need to be discriminated against.

As indicated by the ducting scans, the activity in the system varies with higher deposition rates at expected crud traps. It can be modeled primarily as a line source (more accurately as a twelve-inch wide plane or a twelve-inch wide, one-inch thick slab source) running along the bottom of the center of the duct. The only major point source noted is at the system penetration for the pressure detector instrument (see Figure 2-2 at grid point

Table 2-4 — Ventilation Survey Bottom Center Line.

Grid Column (app.)	Grid Row	o.c. @ point a (mR/hr)	o.c. @ point b (mR/hr)	o.c. @ point c (mR/hr)	Other Significant Points—Location and Distribution of Point	o.c. @ point (mR/hr)
B	1	1.9	2.5	2.4	-	-
B	2	3.4	2.6	2.6	-	-
B	3	2.5	2.4	2.2	-	-
B	4	2.3	2.7	2.2	-	-
B	5	1.9	1.8	2.2	-	-
B	6	4.0	5.0	3.7	bottom center line @ +1.5'	2.8
B	7	4.8	5.0	3.1	bottom center line @ +1.5'	3.6
B	7	-	-	-	bottom center line @ +2.5'	4.9
C	8E	8	5	7	bottom center line @ +1.5'	6
C	8W	-	2.4	3.1	bottom center line @ +1.5'	2.6
C	9	4.8	1.2	1.0	bottom center line @ +0.5'	3.3
C	10	.9	.8	.6	-	-
C	11	.6	.6	.6	-	-
C	12	.5	.5	.5	-	-
C	13	.5	.5	.4	-	-
B	14	.4	.3	.3	-	-
D	9	2.8	3.4	2.7	Instrument Port @ +2.0'	10
E	10	2.5	3.4	3.8	bottom center line @ +0.5'	3.1
F	11	4.0	4.2	4.6	bottom center line @ +2.5'	5.0
G	12	6	7	9	bottom center line @ +1.5'	5.0
H	13	8	6	6	bottom center line @ +1.5'	5.0

See Figure 2-1 for approximate grid locations and points a, b, and c. Surveys were performed with a Bicorn RSO-5 ionization chamber exposure rate meter. The entire length of the ducting was scanned on contact (o.c.) with the highest readings at the bottom of the duct along the axial centerline.

E-9). Although this point is ten mR/hr on contact, it is a point source and as such is a small quantity of activity and smaller contributor to general background relative to the high levels of uniformly distributed activity in the adjacent portions of the ventilation system.

2.3 Shielding Determination

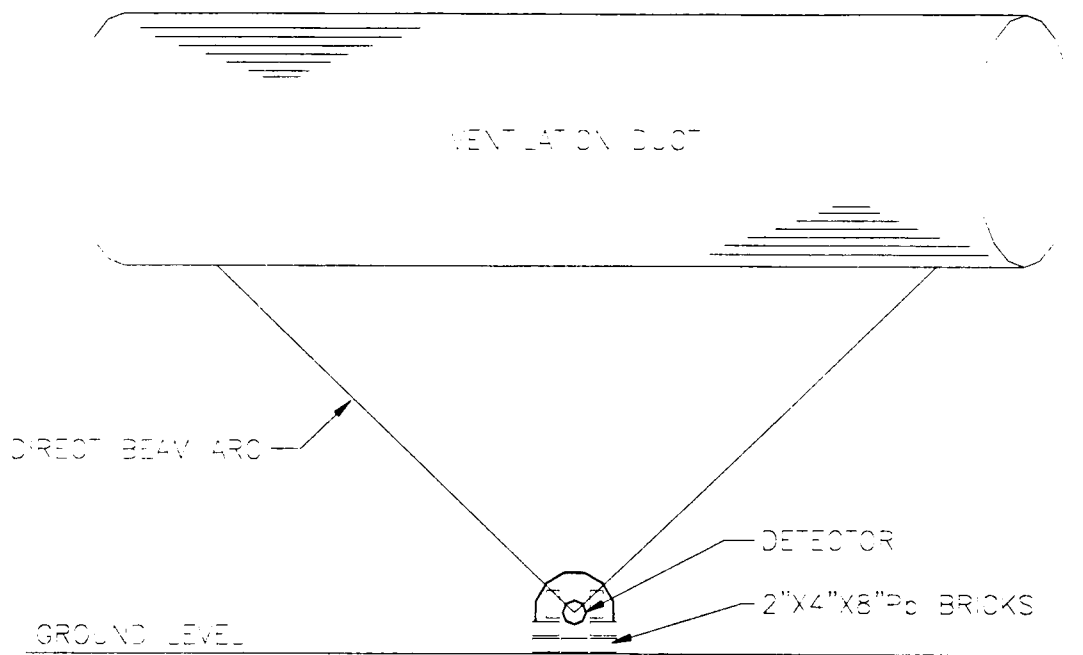
The counting procedure and shield configuration was determined based on: (1) the nature of the primary interference source; (2) its position relative to the system being characterized; (3) the general distribution of activity in the system; and (4) the need to maximize the distance between the probe and the system, to minimize uncertainty due to unknown source distribution. The primary interference source (the hot cells) have thick side shielding, therefore background levels near the roof surface are much lower. The use of two inches of Pb shielding placed on the roof surface reduce any background originating from the hot cells below to approximately one tenth of the actual contribution. Since the ventilation ducting is most accurately characterized as a segmented line source, side shields (two inches of Pb) effectively attenuate background radiation from the portion of ducting not being characterized during a given count. By conducting each count at roof level (four feet from the bottom of the duct), the uncertainties due to source distribution are minimized as are background levels, which was discussed previously.

A readily portable shield composed of nine 2" x 4" x 8" Pb bricks was constructed to shield from the bottom and from three sides (see Figure 2-3). This shield configuration provides a minimum of two inches of Pb shielding to all background sources while allowing an unattenuated path for direct-beam radiation from approximately nine feet of ventilation ducting.

This allows for segmented counting with counts taken every three feet, and a geometrically weighted average applied over the overlapping nine-foot exposed segments. The shielding configuration will be altered slightly at the end-point counting positions to allow a cut-off point for the evaluation. The specific variations are presented in section 3.3.

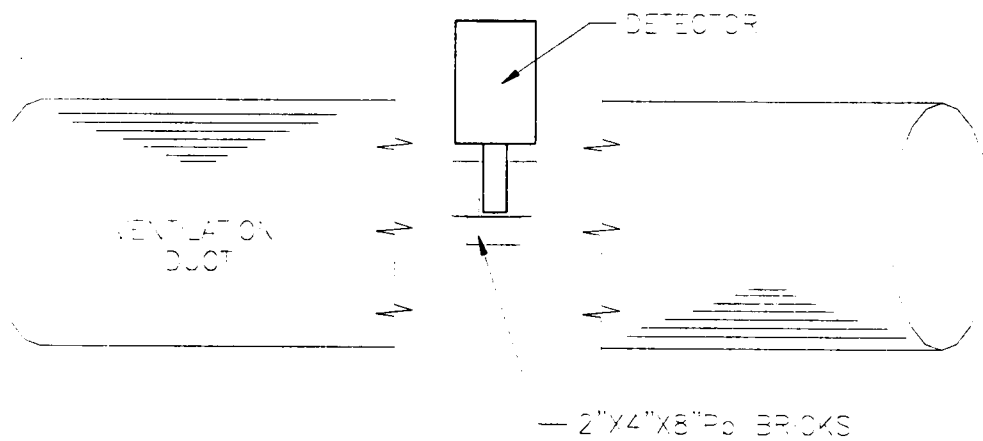
2.4 Background Determination

Though all identified background sources had at least one tenth thickness of shielding in this configuration, attenuated background radiation contributions still had to be evaluated for each counting position. Background counts were performed for the counting position (V-15, see Figure 2-4) nearest the primary background source as an estimation of greatest attenuated background contribution. These counts with the appropriate shielding configuration in place were performed at points equivalently positioned to the primary background source.



ELEVATION VIEW

SCALE: 1/2" = 1'-0"



PLAN VIEW

SCALE: 1/2" = 1'-0"

Figure 2-3 — Standard Counting and Shielding Configuration

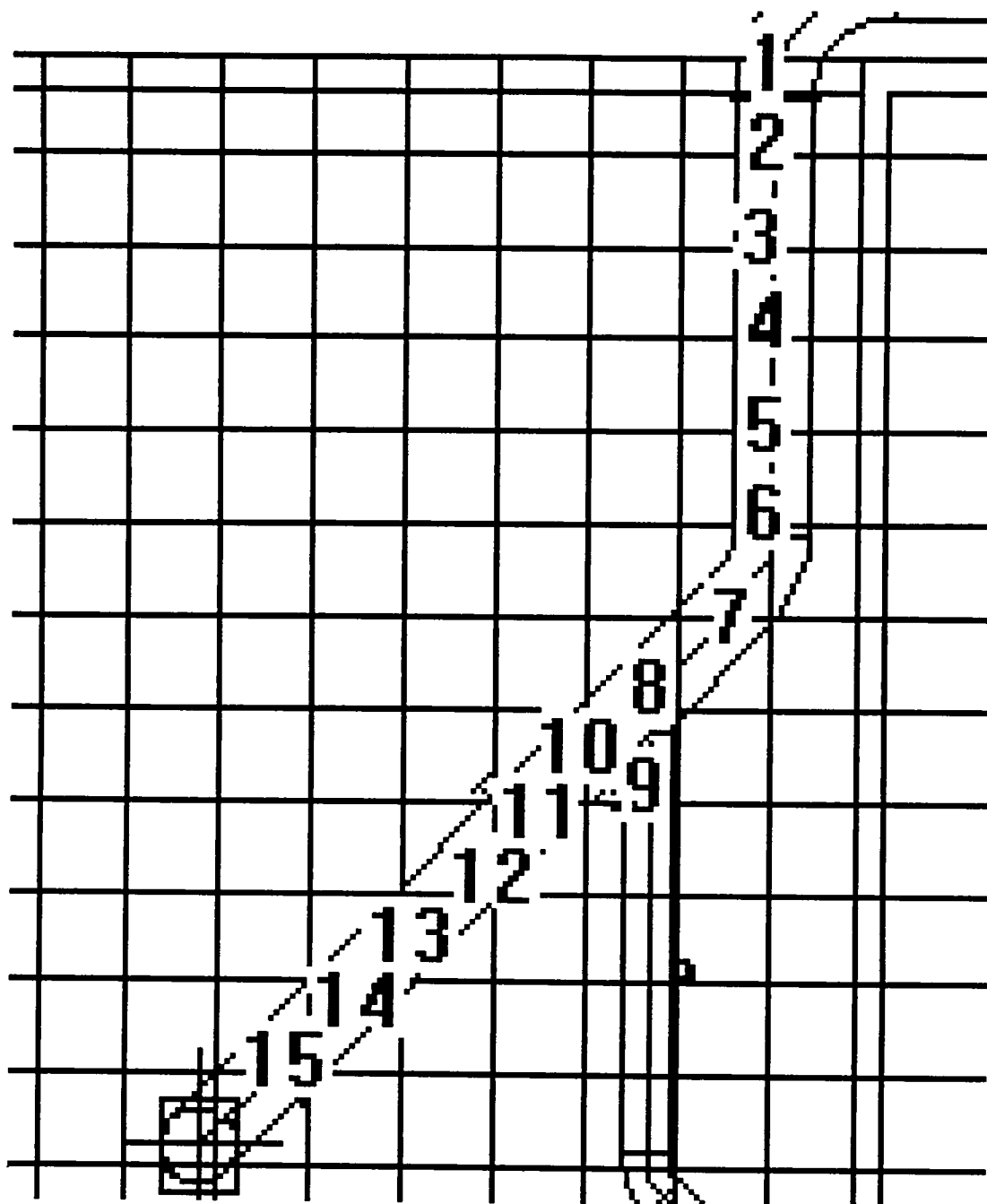


Figure 2-4 — Counting Positions V-1 through V-15. These correspond to both counting positions V-1 through V-15 and ducting segments V-1 through V-15. The counting positions are spaced three feet apart. The ducting segments are three feet long, and centered on the corresponding counting positions.

The values for this "worst case" estimate of contribution showed the attenuated background count rate (2.14 cps) to be less than one-half of a percent of the lowest count rate of any of the fifteen counting positions (448.34 cps at V-4). Attenuated background is a relatively insensitive parameter for this particular application and was therefore considered negligible.

3. EXPERIMENTAL MEASUREMENTS

The counting procedure and activity calculations were based on a segmented line counting procedure. The contaminated portion of the ventilation system was segmented into fifteen equal three-foot segments. Each of the three-foot segments, corresponding to the counting positions V-1 through V-15 (see Figure 2-4), was the focus of a five minute live-time count. The counting position was centered on the corresponding segment. See Appendix A for an example of counting acquisition and analysis for a given counting position.

As discussed in the previous section, a nine-foot length of ducting is visible to each counting position. The three three-foot segments of linearly distributed activity each contribute a geometrically weighted portion of the photons counted at each position (see Figure 3-1). The photon fluence for the focal segment was given a weighting factor

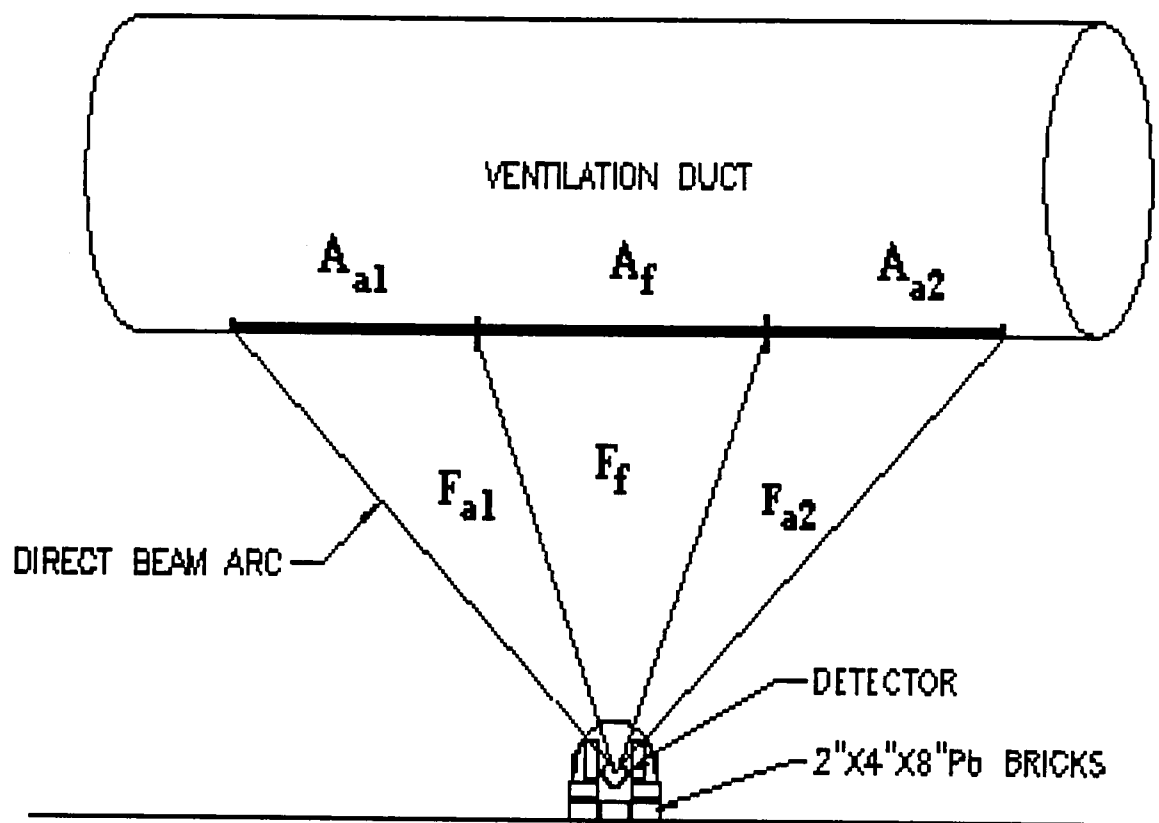


Figure 3-1 — Activity Fluence Contributions to Each Counting Position. The standard configuration is shown for linearly dispersed activity in the three three-foot segments responsible for unattenuated photon fluences at the detector position. The fluences from each of these activity distributions are shown by the unattenuated line-of-sight from the detector to the respective contributing ducting segment.

greater than that given for either of the adjacent segments. These weighting factors are discussed further in the section 4.

3.1 Counting Assumptions

The segmented line source counting procedure was developed using data available from the ducting scans (see Table 2-4) and process knowledge. The process knowledge was acquired from operations and maintenance personnel who had dismantled and replaced portions of the system previously. An assumption of homogeneous source distribution within any three-foot line segment was made allowing the counting procedure to be more practicable. Although the values on Table 2-4 clearly show this not to be a completely accurate assumption, the error introduced by variation of on contact bottom centerline radiation levels for any given three-foot section was addressed during the uncertainty analysis.

The source within the duct was modeled as a twelve-inch wide, one-inch thick homogeneously distributed slab source along the bottom of the duct. Sensitivity analyses of the plausible source distribution models established from the process knowledge and survey data present a minimal error margin from this source distribution model.

3.2 Counting Complications

Excessive detector efficiency was a problem during the counting phase of the process. Although a relatively low efficiency HPGe detector was used (15% relative efficiency), high dead times (from 70% to 100%) were encountered in all counting positions. The shielding configuration helped to reduce the dead time to 50% to 80%, but to ensure accurate evaluation of dead time, and therefore live time and estimated activity, a further reduction of dead time was necessary.

First the conversion gain was changed from 16,384 channels to 4,096 channels. This saved the ADC two comparison steps and still provided sufficient spectrum discrimination for the application. Then since this was not a high resolution application, the pulse-shaping time was changed from long to short, thereby decreasing the pulse-processing time in the pre-amplifier. This was sufficient to reduce the dead time below the manufacturer's recommendation of ten percent for the lower count-rate positions (Knoll 1989). For the higher count-rate positions it was necessary to dial the lower level discriminator up to the Compton edge of the peak being evaluated. The point source efficiency calibration was performed after these adjustments were made.

3.3 Counting Results and Deviations

The counts performed verified the radionuclide of concern to be ^{137}Cs ($^{137\text{m}}\text{Ba}$). No other peaks were noted except the expected background peaks specific to this facility. Results

of the net peak areas and efficiency calibrated equivalent activities for each of the fifteen counting positions are listed on Table 3-1. The efficiency calibration used was calculated based on the results of counting a 370 kBq ^{137}Cs ($^{137\text{m}}\text{Ba}$) point source at a distance of 48" (center-to-center). The apparent activity measurement based on this source distribution was converted to an actual activity measurement which will be discussed in the calculations section.

A few deviations were made from the counting procedure to account for the actual system configuration. The counting procedure presented is for straight lengths of ducting extending into infinity (i.e., there are always adjacent segments on each side). To allow for an end point for the evaluation, the shielding configuration was altered slightly, adding one brick to the configuration on the side to be cutoff. This shielding configuration, which will be referred to as Special Case I, attenuates the direct beam of the segment adjacent to the focal segment on the side which the extra brick is added (see Table 3-1, Counting Position V-1 and V-14 use this configuration to attenuate direct beams from the ducting beyond these cut-off points).

A second change in shielding configuration was made to evaluate the ducting beyond the cutoff point established at V-14. Counting position V-15 evaluates the portion of ducting from the V-14 cutoff point, through the downward curvature to the point at which it penetrates the roof (see Figure 3-2). This counting position is approximately four feet

Table 3-1 — Counting Data from Counting Positions V-1 through V-15.

Counting Position	Net Peak Area at 661.6 keV	Activity Based on Point Source Efficiency Cal.	Shielding Configuration	Counting Segments Visible to the Detector
V-1	166,954	23,540,695 Bq	Special Case I	V-1 & V-2
V-2	168,064	23,697,206 Bq	Standard	V-1, V-2 & V-3
V-3	148,781	20,978,282 Bq	Standard	V-2, V-3 & V-4
V-4	134,503	18,965,069 Bq	Standard	V-3, V-4 & V-5
V-5	157,472	22,203,722 Bq	Standard	V-4, V-5 & V-6
V-6	199,610	28,145,227 Bq	Standard	V-5, V-6 & V-7
V-7	231,055	32,579,006 Bq	Standard	V-6, V-7 & V-8
V-8	308,456	43,492,631 Bq	Standard	V-7, V-8, V-9 & V-10
V-9	222,981	31,440,563 Bq	Standard	V-8, V-9 & V-10
V-10	243,413	34,321,497 Bq	Standard	V-8, V-9, V-10 & V-11
V-11	187,019	26,369,882 Bq	Standard	V-10, V-11 & V-12
V-12	170,897	24,096,662 Bq	Standard	V-11, V-12 & V-13
V-13	202,768	28,590,508 Bq	Standard	V-12, V-13 & V-14
V-14	254,518	35,887,314 Bq	Special Case I	V-13 & V-14
V-15	451,914	63,720,365 Bq	Special Case II	V-15

These values were provided by the GammaVision 2.25 counting acquisition and analysis software package. The activities shown are the activities provided by the software based on the respective net peak area, a 300 second live-time count, the gamma yield for the 661.6 keV photon for ^{137}Cs , and a point source efficiency calibration for the 661.6 keV energy at 48".

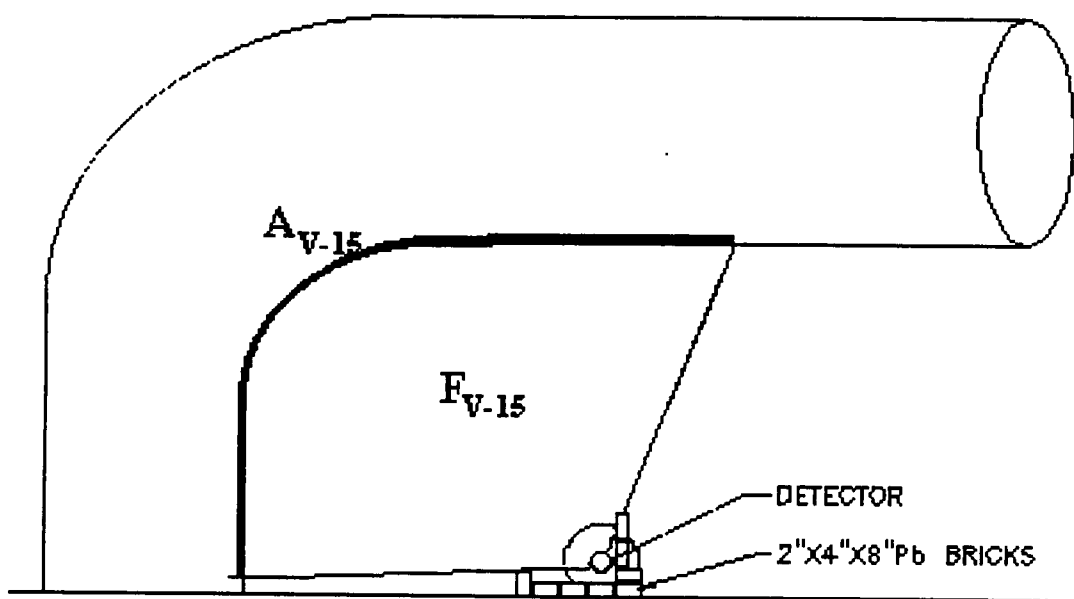


Figure 3-2 — Counting Position V-15 and Special Case II Shielding Configuration.
The special case II configuration is shown for linearly dispersed activity in the nine-foot segment responsible for unattenuated photon fluences at detector position V-15. The fluence from this activity distribution is shown by the unattenuated line-of-sight from the detector to the ducting segment.

from all points on the line which runs along the bottom centerline of the arc created by the ducting here. This second change in shielding configuration, Special Case II, attenuates any direct beams from below and one side allowing the side curving to the roof penetration to be characterized.

A third change in the counting procedure uses the standard shielding configuration, but accounts for the fork in the ducting where the room ventilation line feeds into the system. The number of three-foot segments visible to counting positions V-8 and V-10 is four, and the arrangements of the ducting segments with respect to the detector are different than the standard configuration for V-8, V-9, and V10. These differences will each be discussed further in the section 4.

4. COMPUTATIONAL METHODS AND RESULTS

There are many calculations involved in converting the counting data from Table 3-1 into an accurate estimation of the actual activity in the ventilation duct. The results of the first few steps have already been presented as the point source activity estimation listed in Table 3-1. This value was provided by the GammaVision 2.25 acquisition and analysis software and based on a very simple efficiency calibration. The steps leading to this value are presented for completeness.

The first step in calculating the activity in the portion of ducting counted is to calculate the net peak area count rate reduced by the background value net peak area count rate, or what will be referred to hereafter as the true net count rate. The true net count rate for a given peak is given by

$$R_N = [(C_N / t_C) - (B_N / t_B)] \quad (4-1)$$

where

R_N = the true net count rate for the given peak;

C_N = the net area for the given peak;

t_C = the count time for that counting position;

B_N = the net area for the background count (or average for multiple background counts) for the given peak; and

t_B = the count time for the background count(s).

As previously discussed, the background count rate will be considered negligible in this example. Therefore, for this case, the true net count rate can be given by

$$R_N = C_N / t_C \quad (4-2)$$

The true net count rate can be converted to an observed point source activity by completing a point source efficiency calibration at, or encompassing, the peak energy .

The activity observed at a given counting position based on the point source efficiency calibration at that energy is given by

$$A_P = R_N / (\epsilon_P Y) \quad (4-3)$$

where

A_P = the observed activity of the suspect nuclide based on the point source efficiency at that energy;

R_N = the true net count rate for the given peak;

ϵ_P = the efficiency for the given energy calculated from the point source activity at a given distance; and

Y = the gamma yield of the suspect nuclide at the given energy.

This A_P value is the activity listed in Table 3-1.

To convert this point source activity estimate to an accurate representation of activity in the section of ducting being counted (A_D), it is useful to relate the point source efficiency (ϵ_P) to the actual efficiency for the counting position (ϵ_D). Replacing the point source efficiency based activity (A_P) and point source efficiency (ϵ_P) terms in equation 4-3, with A_D and ϵ_D , then

$$A_D = R_N / (\epsilon_D Y). \quad (4-4)$$

Since Y is constant, then for any given count rate (R_N)

$$A_P \epsilon_P = (R_N / Y) = A_D \epsilon_D$$

or

$$A_P \epsilon_P = A_D \epsilon_D . \quad (4-5)$$

To actually compare ϵ_P to ϵ_D it is necessary to compare efficiency to the photon fluence rate (F). Net count rate can be redefined as

$$R_N = F_P k_{e1} \quad (4-6)$$

where

F_P = the fluence rate, at the detector, for the point source activity and geometry during the efficiency calibration; and

k_{e1} = a constant representing the effective detector size including an efficiency factor for photons passing through the detector for the given peak energy.

Redefining the net count rate in equation 4-3 with the terms in equation 4-6, then

$$A_P = (F_P k_{e1}) / (\epsilon_P Y) \quad (4-7)$$

where

F_P = the photon fluence at the detector position for the calibration geometry.

Rearranging this for efficiency, and replacing estimated activity with the calibration activity upon which the fluence rate is based, then

$$\epsilon = (F k_{e1}) / (A_{cal} Y) \quad (4-8)$$

where

A_{cal} = the activity used to calculate the fluence rate in any given geometry and source and shielding distribution.

By using the same calibration activity to calculate the fluence rates at the detector positions for both the point source and actual geometry and source distribution, then the respective efficiencies can be described by

$$\epsilon_P = (F_P k_{e1}) / (A_{cal} Y) , \quad (4-9)$$

and

$$\epsilon_D = (F_D k_{e1}) / (A_{cal} Y), \quad (4-10)$$

where

F_P = the fluence rate calculated for the point source activity and geometry used in the efficiency calibration; and

F_D = the fluence rate calculated for the total observed length based on estimated shielding, source distribution (with the total source activity equal to the efficiency calibration activity), and geometry.

Thus

$$\epsilon_P / F_P = (k_{e1}) / (A_{cal} Y) = \epsilon_D / F_D ,$$

or

$$F_P / \epsilon_P = F_D / \epsilon_D . \quad (4-11)$$

Multiplying equation 4-5 by equation 4-11, then

$$(A_P \epsilon_P) (F_P / \epsilon_P) = (A_D \epsilon_D) (F_D / \epsilon_D) ,$$

or

$$A_P F_P = A_D F_D . \quad (4-12)$$

Thereby, the observed point source activity can be converted to an actual activity estimate by multiplying by a correction factor which accounts for shielding, source distribution and counting geometry. To do this, MicroShield 4.2 was used to calculate photon fluence rates ($\gamma / \text{cm}^2 \text{ sec}$) for photons at the peak energy (i.e., without buildup) at the detector position.

Since an overlapping segmented counting procedure is being used to smooth the estimated linear activity, it is necessary to break the fluence rate calculated for the total observed length into the three segments observed in that counting position. The total fluence observed by the detector can be broken down such that

$$F_D = F_{a1} + F_f + F_{a2} \quad (4-13)$$

where

F_D = the fluence rate calculated for the total observed length;

F_{a1} = the fluence rate for the present geometry of the first adjacent segment;

F_f = the fluence rate for the present geometry of the current segment; and

F_{a2} = the fluence rate for the present geometry of the second adjacent segment.

It is important, at this point, to emphasize that to validate equation 4-11, the total of the activity used to calculate F_{a1} plus the activity used to calculate F_f plus the activity used to calculate F_{a2} must equal the activity used to calculate F_D which also must equal the activity used to calculate F_P . Therefore the activity observed by the detector can be more accurately represented by

$$A_D (F_{a1} + F_f + F_{a2}) = A_P F_P. \quad (4-14)$$

The first adjacent segment's contribution to the activity estimated from a given counting position, assuming a certain amount of linear homogeneity, can be estimated as

$$A_D F_{a1} = A_P F_P - A_D F_f - A_D F_{a2}. \quad (4-15)$$

This weighted activity estimator is only a portion of the activity assigned to a given segment. To gain an accurate estimation, this term ($A_D F_{a1}$) must be added to the other terms representing this segment's contribution to the other applicable counting positions. Then by dividing by the F_D term, the activity of a given segment can be calculated. A leap is now made between focusing on the counting positions to focusing on the segments of ducting. The end goal is to determine the amount of activity in the ducting system. Since this to be done piece-wise, the next item of interest is how much activity is in a segment of the system. Through this method, the activity in a given segment (S) can be given by (next page)

$$A_S = [(F_{a2(S-1)} A_{D(S-1)}) + (F_{f(S)} A_{D(S)}) + (F_{a1(S+1)} A_{D(S+1)})] / F_D$$

or

$$A_S = [(F_P F_{a2(S-1)} A_{P(S-1)}) / F_D^2] + [(F_P F_{f(S)} A_{P(S)}) / F_D^2] + [(F_P F_{a1(S+1)} A_{P(S+1)}) / F_D^2] \quad (4-16)$$

where

A_S = the activity in a given segment of ducting;

$F_{a2(S-1)}$ = the second adjacent segment fluence calculated for the counting position focused on the first adjacent segment to S;

$A_{P(S-1)}$ = the activity based on the point source efficiency for the counting position focused on the first adjacent segment to S;

$F_{f(S)}$ = the focused segment fluence calculated for the counting position focused on segment S;

$A_{P(S)}$ = the activity based on the point source efficiency for the counting position focused on segment S;

$F_{a1(S+1)}$ = the first adjacent segment fluence calculated for the counting position focused on the second adjacent segment to S; and

$A_{P(S+1)}$ = the activity based on the point source efficiency for the counting position focused on the first adjacent segment to S.

The activity assigned to any given segment is a weighted average of that segment's contribution to each counting position to which it has an unattenuated direct beam.

Example

The counts performed at V-2, V-3 and V-4 resulted in estimated activities of 23,697,206 Bq, 20,978,282 Bq, and 18,965,069 Bq respectively based on the 370 kBq point source at

four feet. MicroShield 4.2 was used to approximate the peak energy photon fluence for a 370 kBq source at four feet resulting in $1.665 \text{ } \gamma/\text{cm}^2\text{sec}$. MicroShield 4.2 was also used to approximate three other peak energy photon fluences; two for a 123.33 kBq source ($370/3 = 123.33$ — assuming even distribution over the contributing three segments) homogeneously distributed through a three-foot long, twelve-inch wide, and one inch deep metal-oxide slab with one tenth of an inch of steel shielding at a normal distance of four feet from the outer edge of the shielding; and the third for a nine-foot long 370 kBq source distributed as the other two. One of these represented the current counting, or focal, segment (applicable to V-2, V-3, or V-4) and was therefore centered on the four-foot normal line to the detector. The result was $.37433 \text{ } \gamma/\text{cm}^2\text{sec}$. The second represented the adjacent segments (V-2, V-3 or V-4). The center was therefore offset three feet perpendicular to the four-foot normal line from the detector. The result was $.240733 \text{ } \gamma/\text{cm}^2\text{sec}$. The nine-foot segment was centered as the first, resulting in a fluence rate of $.8558 \text{ } \gamma/\text{cm}^2\text{sec}$.

Therefore the activity in V-3 can be determined by

$$A_{V-3} = (F_P F_{a2(V-2)} A_{P(V-2)}) / F_D^2 + (F_P F_{f(V-3)} A_{P(V-3)}) / F_D^2 + (F_P F_{a1(V-4)} A_{P(V-4)}) / F_D^2$$

where

$$F_{a2(V-2)} = .240733 \text{ } \gamma/\text{cm}^2\text{sec} ;$$

$$A_{P(V-2)} = 23,697,206 \text{ Bq};$$

(next page)

$$F_P = 1.665 \gamma/\text{cm}^2\text{sec};$$

$$F_{f(V-3)} = .374333 \gamma/\text{cm}^2\text{sec};$$

$$A_{P(V-3)} = 20,978,282 \text{ Bq};$$

$$F_{a1(V-4)} = .240733 \gamma/\text{cm}^2\text{sec}; \text{ and}$$

$$A_{P(V-4)} = 18,965,069 \text{ Bq}.$$

$$F_D = .8558 \gamma/\text{cm}^2\text{sec}$$

Therefore the three foot segment of ducting V-3 is estimated to have

$$A_{V-3} = 41,200,473 \text{ Bq}.$$

End of Example

This method for calculating activity contained in a given section of ducting could be directly applied to segments V-2 through V-7 and V-11 through V-13. The results are listed in Table 4-1. Segment V-9 also used equation 4-16, but while the equation is an accurate representation, the geometry specifically involved is slightly different. The geometry for segments V-1 and V-14 is the same as the standard geometry, except that one adjacent segment has been eliminated from the equation, therefore the equation for activity in end point segments (i.e., segments whose focal counting position shielding configuration is special case I) can be expressed by

$$A_S = [(F_P F_{a2(S\pm1)} A_{P(S\pm1)}) / F_D^2] + [(F_P F_{f(S)} A_{P(S)}) / F_D^2]. \quad (4-17)$$

Table 4-1 — Activity Estimate of ^{137}Cs ($^{137\text{m}}\text{Ba}$) in MRV Ducting on the West Roof of the RDF.

Ducting Segment	Point Source Activity	Contributing Counts	Activity Equation	Estimated Activity
V-1	23,540,695 Bq	V-1 & V-2	4-17	42,594,029 Bq
V-2	23,697,206 Bq	V1-V3	4-16	44,530,398 Bq
V-3	20,978,282 Bq	V2-V4	4-16	41,200,473 Bq
V-4	18,965,069 Bq	V3-V5	4-16	39,771,670 Bq
V-5	22,203,722 Bq	V4-V6	4-16	44,677,613 Bq
V-6	28,145,227 Bq	V5-V7	4-16	53,932,750 Bq
V-7	32,579,006 Bq	V6-V8	4-16	66,930,281 Bq
V-8	43,492,631 Bq	V7-V10	4-18	68,123,816 Bq
V-9	31,440,563 Bq	V8-V10	4-16	69,341,589 Bq
V-10	34,321,497 Bq	V8-V11	4-18	63,486,134 Bq
V-11	26,369,882 Bq	V10-V12	4-16	54,411,518 Bq
V-12	24,096,662 Bq	V11-V13	4-16	50,584,662 Bq
V-13	28,590,508 Bq	V12-V14	4-16	57,158,197 Bq
V-14	35,887,314 Bq	V-13 & V-14	4-17	59,611,167 Bq
V-15	63,720,365 Bq	V-15	4-19	94,474,094 Bq
Total				851 MBq

The point source efficiency calibrated activity estimate given by the GammaVision 2.25 software has been corrected for source geometry and shielding by the respective activity equation. The estimated activity for a given segment is a weighted average of the activities estimated at each of the listed contributing counting positions.

In the case of the special geometry presented by segments V-8 and V-10, the geometry includes four counting position inputs instead of three. Also, the fourth counting position is in a slightly different geometrical configuration, which is accounted for in the fluence rate contribution factor. The equation for activity in these two segments is given by

$$A_S = [(F_P F_{a2(S-1)} A_{P(S-1)}) / F_D^2] + [(F_P F_{f(S)} A_{P(S)}) / F_D^2] \\ + [(F_P F_{a1(S+1)} A_{P(S+1)}) / F_D^2] + [(F_P F_{a2(S+2)} A_{P(S+1)}) / F_D^2] . \quad (4-18)$$

In the case of the special geometry presented by segment V-15, a new approximation was made. The design of the downward curve of the ducting in this segment was such that the bends approximately form three three-foot segments, connected end-to-end, but at such an angle that a line, normal to the bottom centerline and four feet in length, could be projected from the center of each three-foot segment to the center of the detector. The resulting fluence contribution at the detector due to each of these segments is the same and equal to the fluence due to the focal segment in the standard case. Adding these three fluences and dividing by three results in the fluence rate for a focal segment but calculated using the entire calibration activity. The resulting equation for activity in this segment is given by

$$A_S = (F_P A_{P(S)}) / F_D . \quad (4-19)$$

The resultant activity in the portion of the Main Radioactive Ventilation Header above the 3019B wing of the Radiochemical Development Facility is listed in Table 4-1. This

activity is listed, as calculated, for each segment and as the sum of the segments. This sum value, 851 MBq, is the total activity estimate for the portion of the header characterized.

5. UNCERTAINTY ANALYSIS

The uncertainty associated with the calculated activity estimate was modeled from all plausible sources of error, and analyzed using a Latin Hypercube Sampling (LHS) process provided by Crystal Ball 3.0, and propagation of error formulas. The equations used to estimate the activities were run through the LHS with the variable input parameters. The distribution of potentially sensitive parameters was modeled from all available data and process knowledge. Each major parameter (fluence rate error, count rate variability, and the linear homogeneity assumption) has been analyzed, and its input calculated into the overall activity uncertainty.

5.1 Fluence Rate Uncertainty

The input parameters for fluence rate are sediment height and attenuation coefficient, duct thickness and attenuation coefficient, and source position within the sediment, both axially and radially. These parameters were assigned appropriate distributions, and the equation for the fluence rate at the detector position based on the efficiency calibration source activity was evaluated.

For the nine-foot segment evaluated by the detector in the standard shielding configuration, the fluence rate equation (Turner 1992) is

$$F_D = A_{cal} \exp[(\mu_D r_D) + (\mu_S r_S)] / [(X_T^2 + Y_T^2 + Z_T^2) (4 \pi k_c^2)] \quad (5-1)$$

where

- μ_D = the attenuation coefficient (in inches⁻¹) for the duct;
- r_D = the distance (in inches) the photon travels through the duct;
- μ_S = the attenuation coefficient (in inches⁻¹) for the sediment;
- r_S = the distance (in inches) the photon travels through the sediment;
- X_T = the total vertical component of the distance (in inches) from the detector center to a point source;
- Y_T = the horizontal centerline offset component of the distance (in inches) from the detector center to a point source;
- Z_T = the horizontal centerline axial component of the distance (in inches) from the detector center to a point source; and
- k_c = conversion factor from cm to inches.

Each of these terms (except k_c) are parameters which have an associated uncertainty.

The ducting attenuation coefficient (μ_D) is the product of mass attenuation coefficient and the density. The mass attenuation coefficient for Fe at 661.6 keV (.072874 cm²/g using linear interpolation) was multiplied by the density for steel (7.8 g/cm³) resulting in a value

of $.5684172 \text{ cm}^{-1}$ or 1.4438 in^{-1} (Shleien 1992). The value used by MicroShield 4.2 was determined to be 1.45 in^{-1} . Since the ducting is stainless steel, not pure Fe or steel, these values are not exact, but are very close. Therefore the distribution for this parameter was modeled as a normal distribution with a mean of 1.45 in^{-1} and a standard deviation of $.01 \text{ in}^{-1}$.

The sediment attenuation coefficient (μ_s) is the product of mass attenuation coefficient and the density. The mass attenuation coefficient for Fe at 661.6 keV ($.072874 \text{ cm}^2/\text{g}$ using linear interpolation) was used based on verbal reports, and laboratory analyses of the material from the 1988 replacement of a section of the header. These reports agreed that the material was a dirt-like substance primarily composed of iron oxide rust particles. This value multiplied by the center of the range of densities listed for dirt (1.7 g/cm^3) resulting in a value of $.1238858 \text{ cm}^{-1}$ or $.314670 \text{ in}^{-1}$ (Shleien 1992). The value used by MicroShield 4.2 (based on the dirt density of 1.7 g/cm^3) was determined to be $.31 \text{ in}^{-1}$. These parameters, mass attenuation coefficient and density, are each highly variable. Therefore the distribution for this parameter was modeled as a normal distribution with a mean of $.31 \text{ in}^{-1}$ and a standard deviation of $.06 \text{ in}^{-1}$.

The distance the photon travels through the duct (r_D) is based on the position of the point source in the duct (X_T , Y_T , and Z_T) and on the duct thickness (T_D), and is given by

$$r_D = T_D (X_T^2 + Y_T^2 + Z_T^2)^{1/2} / X_T. \quad (5-2)$$

System design specifications list the duct thickness as approximately one tenth of an inch. This value is not exact, but very close dependent on the construction standards used to meet the design specifications. Therefore the distribution for this parameter was modeled as a triangular distribution with a likeliest value of .1 inch and a minimum and maximum of .09 and .11 inch respectively.

The distance the photon travels through the sediment (r_S) is based on the position of the point source in the duct (X_T , Y_T , and Z_T) and on the sediment thickness beneath the point source (T_S), and is given by

$$r_S = T_S (X_T^2 + Y_T^2 + Z_T^2)^{1/2} / X_T. \quad (5-3)$$

The sediment thickness is most easily approximated by multiplying two other variable and unknown parameters, total sediment thickness (T_T) and the ratio of the point source elevation above the duct to the total sediment thickness (K_S), such that

$$T_S = T_T K_S. \quad (5-4)$$

Verbal reports, from the operators and maintenance personnel who dismantled the system in 1988, stated the total sediment thickness (T_T) to be from zero to three inches deep centered along the bottom of the pipe and, to a lesser extent, up the sides of the pipe. The vast majority was reported to be within six inches of the centerline and almost all of the material within one foot of centerline. Therefore the distribution for this parameter was modeled as a triangular distribution with a likeliest value of one inch and a minimum and maximum of zero and three inches respectively.

The ratio of the point source elevation above the duct to the total sediment thickness (K_S) is assumed to be relatively homogeneous. There is no process knowledge to validate any assumptions of stratification of the activity in any portion of the sediment. Since the sediment itself is the transport mechanism for the radioactive isotopes, an assumption of uniformity is considered appropriate. This parameter is therefore modeled as a uniform distribution from zero to one.

The position of the point source in the duct relative to the detector center (X_T , Y_T , and Z_T) is the product of several variable input parameters. The total vertical component of the distance (in inches) from the detector center to a point source in the duct is given by

$$X_T = 48'' + [18'' - (18''^2 - Y_T^2)^{1/2}] + T_S + T_D. \quad (5-5)$$

The horizontal centerline axial component is modeled homogeneously, since there is no direct reason for more deposition in one part of a straight length of ducting than another.

The variable parameter Z_i was modeled as a uniform distribution from zero to nine feet, and

$$Z_T = (4.5' - Z_i) \text{ 12 inches/foot.} \quad (5-6)$$

The horizontal centerline offset component is modeled based on the sediment deposition discussed in the section on sediment thickness. The variable parameter Y_i was modeled as a normal distribution with a mean of 1.5' and a standard deviation of .3', and

$$Y_T = (1.5' - Y_i) \text{ 12 inches/foot.} \quad (5-7)$$

The LHS simulation was conducted on this data. After 10,000 trials, the fluence rate for the standard configuration was determined to have a mean of .83 $\gamma/\text{cm}^2\text{sec}$ and a standard deviation of .28 $\gamma/\text{cm}^2\text{sec}$. The MicroShield 4.2 value of .8558 $\gamma/\text{cm}^2\text{sec}$ is inherently biased due to the simplified 12" by 1" by 9' rectangular slab approximation made to fit one of the available MicroShield 4.2 geometries. This bias of -3.1% is acceptable based on the levels of error associated with this analysis. From the results of this uncertainty analysis, the Fluence Rate calculation performed on MicroShield 4.2 has an accuracy, due to plausible distribution and shielding errors, of plus 57% and minus 60% with a 95% confidence factor.

A sensitivity analysis was also run by Crystal Ball 3.0 along with the LHS run. The results are displayed in Figure 5-1. Note that the major sensitivity parameters are sediment depth and source position within the sediment. An order of magnitude less is the sediment attenuation coefficient parameter, and the other parameters including radial and axial distribution are an order of magnitude less than that.

The axial and radial distribution parameters were intentionally minimized during the counting procedure development by maximizing the distance between the detector and the duct and using an overlapping segmented counting procedure. While fluence rate uncertainty and sensitivity analyses were performed using LHS for each configuration, the standard configuration has the greatest axial variability. Therefore the error due to axial distribution is at its maximum in this standard configuration. Since axial distribution is an insensitive parameter in this configuration, the fluence rate uncertainty analyses performed for the other three configurations will not be discussed in detail. Also since axial distribution is an insensitive parameter, the question of uncertainty due to the linear homogeneity assumption can be considered negligible.

5.2 Activity Uncertainty

Uncertainties due to the naturally variable process of radioactivity were integrated into the overall activity estimate uncertainty. This was accomplished analytically by using the

Sensitivity Chart

Target Forecast: Fluence

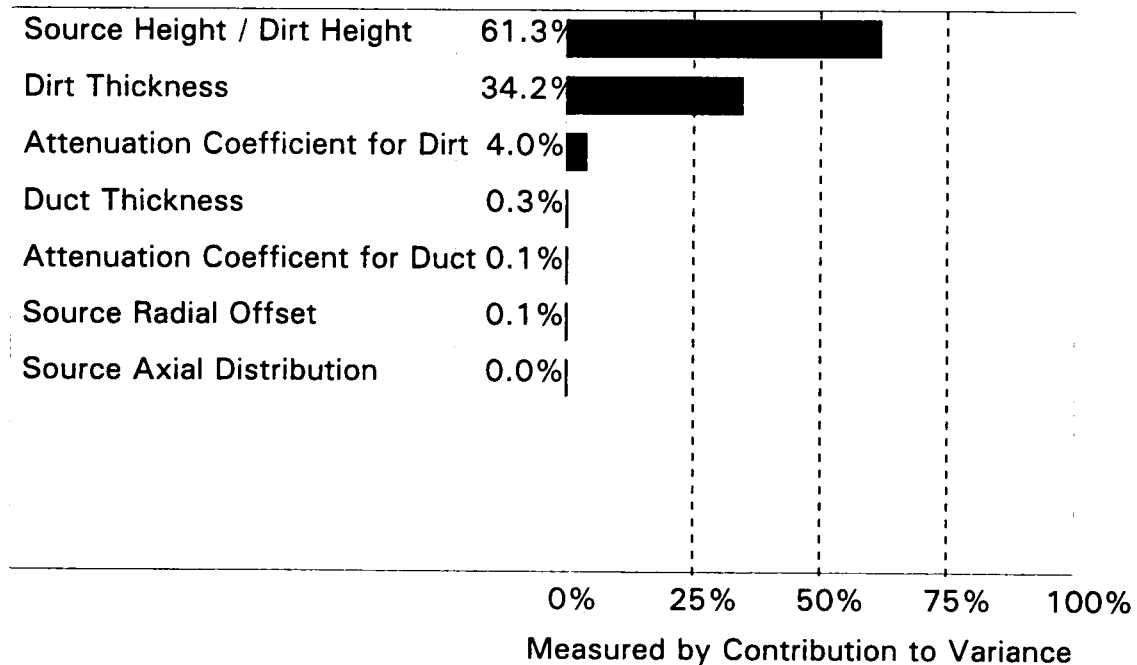


Figure 5-1 — Fluence Rate Sensitivity Analysis Results. This is a measurement of the relative sensitivity of the variable parameters in the equation used to calculate the fluence rate at the detector from a linearly homogeneous nine-foot length of ducting in the standard counting configuration. The sensitivity analysis was provided by Crystal Ball 3.0 as an output of the LHS run to measure fluence rate uncertainty.

propagation of error formula on the means and standard deviations of the parameters of equation 4-16. The means and standard deviations for each of the fluence terms were determined by the LHS technique described in the previous section.

The means and standard deviations for the natural variability of radioactivity was estimated using the normal distribution. This approximation is easily justified by the high count rates in this application. Thus

$$\mu_{\text{Act}} = \text{Activity}$$

and

$$\sigma_{\text{Act}} = (\text{Activity})^{1/2}.$$

Given these values and the equation for propagation of error, the following equations can be developed from equation 4-16. Rearranging equation 4-16 such that

$$A_S = [(F_P F_{a2(S-1)} A_{P(S-1)}) / F_D^2] + [(F_P F_{f(S)} A_{P(S)}) / F_D^2] \\ + [(F_P F_{a1(S+1)} A_{P(S+1)}) / F_D^2]$$

becomes

$$A_S = A_{T1} + A_{T2} + A_{T3} \quad (5-8)$$

where

A_{T1} = the activity contribution from the first offset counting position;

A_{T2} = the activity contribution from the focal counting position;
and (next page)

A_{T3} = represents the activity contribution from the second offset counting position.

Therefore the mean of the activity in the given segment (μ_{AS}) can be expressed as

$$\mu_{AS} = \mu_{AT1} + \mu_{AT2} + \mu_{AT3} . \quad (5-9)$$

The standard deviation of the activity in the given segment is given by applying the propagation of error formula (Beers 1953) to equation 5-8.

Therefore

$$\sigma_{AS} = (((\delta A_s / \delta A_{T1})^2 \sigma_{AT1}^2) + ((\delta A_s / \delta A_{T2})^2 \sigma_{AT2}^2) + ((\delta A_s / \delta A_{T3})^2 \sigma_{AT3}^2))^{1/2} \quad (5-10)$$

can be solved such that

$$\sigma_{AS} = (\sigma_{AT1}^2 + \sigma_{AT2}^2 + \sigma_{AT3}^2)^{1/2}. \quad (5-11)$$

Since each activity contribution term (A_T) is composed such that

$$A_T = (F_P F_T A_P) / F_D^2 ,$$

then

$$\mu_{AT} = (\mu_{FP} \mu_{FT} \mu_{AP}) / \mu_{FD}^2 , \quad (5-12)$$

and

$$(\sigma_{AT} / \mu_{AT})^2 = (\sigma_{FP} / \mu_{FP})^2 + (\sigma_{FT} / \mu_{FT})^2 + (\sigma_{AP} / \mu_{AP})^2 + (\sigma_{FD} / \mu_{FD})^2 ,$$

or (next page)

$$\sigma_{AT}^2 = \mu_{AT}^2 [(\sigma_{FP} / \mu_{FP})^2 + (\sigma_{FT} / \mu_{FT})^2 + (\sigma_{AP} / \mu_{AP})^2 + 2 (\sigma_{FD} / \mu_{FD})^2]. \quad (5-13)$$

Example

Applying the information in Table 5-1 to equations 5-9, 5-11, 5-12 and 5-13, the mean activity and its associated standard deviation can be calculated for segment V-4. The mean activity for segment V-4 can be given by

$$\mu_A = ((\mu_{FP} \mu_{Fa2} \mu_{AV-3}) / \mu_{FD}^2) + ((\mu_{FP} \mu_{FS} \mu_{AV-4}) / \mu_{FD}^2) + ((\mu_{FP} \mu_{Fa1} \mu_{AV-5}) / \mu_{FD}^2).$$

Using the mean values LHS calculated for the fluence rates, the mean value for the activity in segment V-4 is 40.51 MBq as compared to 39.77 MBq calculated using the MicroShield 4.2 calculated fluence rates. The magnitude of error between the LHS mean and the calculated estimate is very small. The uncertainty associated with the LHS mean is considerably greater.

The standard deviation of the activity estimate of ducting segment V-4 can be calculated by

$$\begin{aligned} \sigma_A = & ((\mu_{AV-3}^2 ((\sigma_{FP} / \mu_{FP})^2 + (\sigma_{Fa2} / \mu_{Fa2})^2 + (\sigma_{AP(V-3)} / \mu_{AP(V-3)})^2 + 2 (\sigma_{FD} / \mu_{FD})^2)) + \\ & (\mu_{AV-4}^2 ((\sigma_{FP} / \mu_{FP})^2 + (\sigma_{FF} / \mu_{FF})^2 + (\sigma_{AP(V-4)} / \mu_{AP(V-4)})^2 + 2 (\sigma_{FD} / \mu_{FD})^2)) + \\ & (\mu_{AV-5}^2 ((\sigma_{FP} / \mu_{FP})^2 + (\sigma_{Fa1} / \mu_{Fa1})^2 + (\sigma_{AP(V-5)} / \mu_{AP(V-5)})^2 + 2 (\sigma_{FD} / \mu_{FD})^2)))^{1/2}. \end{aligned}$$

Table 5-1 — Uncertainty Terms.

Term	Approximate Distribution	Method of Calculation	Mean	Standard Deviation
F_P	Point	Analytical	1.665	0
F_{a2(S-1)}	Lognormal	LHS/ MicroShield	.23/ .240733	.07
F_{f(S)}	Lognormal	LHS/ MicroShield	.36/ .374333	.07
F_D	Lognormal	LHS/ MicroShield	.83/ .8558	.28
F_{a1(S+1)}	Lognormal	LHS/ MicroShield	.23/ .240733	.07
A_{V-3}	Normal	Poisson App.	20978282	4580
A_{V-4}	Normal	Poisson App.	18965069	4355
A_{V-5}	Normal	Poisson App.	22203723	4712

These are the MicroShield 4.2 and Crystal Ball 3.0 LHS results for the fluence rates in equation 4-16. Also listed are examples of the variations due to radioactivity based on the normal approximation of radioactive variability. Please note there is no listed uncertainty in the point source geometry fluence rate. This will automatically cause this term to fall out of the segment activity standard deviation term.

Applying the Table 5-1 values to the above equation results in a standard deviation for segment V-4 of 34.5 MBq.

End of Example

The mean and standard deviation calculations were repeated for each segment.

Analytical evaluation of propagation of error and LHS techniques were used. The results of the calculated values based on the MicroShield 4.2 fluence rates, and the LHS and analytically calculated means and standard deviation are listed for each segment in Table 5-2.

The mean value of the total activity in table 5-2 is given by a simple summation of the means. That is

$$\begin{aligned}\mu_{A(\text{Total})} = & \mu_{AV-1} + \mu_{AV-2} + \mu_{AV-3} + \mu_{AV-4} + \mu_{AV-5} + \mu_{AV-6} \\ & + \mu_{AV-7} + \mu_{AV-8} + \mu_{AV-9} + \mu_{AV-10} \\ & + \mu_{AV-11} + \mu_{AV-12} + \mu_{AV-13} + \mu_{AV-14} + \mu_{AV-15}.\end{aligned}\tag{5-14}$$

Therefore the LHS derived mean activity is 872 MBq.

Table 5-2 — Activity Uncertainties.

Segment	Calculated Activity (MShield)	Estimated Mean (LHS)	Standard Deviation (LHS)
V-1	42.6 MBq	42.8 MBq	12.4 MBq
V-2	44.5 MBq	45.4 MBq	35.9 MBq
V-3	41.2 MBq	42.0 MBq	35.8 MBq
V-4	39.8 MBq	40.5 MBq	34.5 MBq
V-5	44.7 MBq	45.5 MBq	36.8 MBq
V-6	53.9 MBq	54.9 MBq	43.5 MBq
V-7	66.9 MBq	68.2 MBq	51.8 MBq
V-8	68.1 MBq	72.4 MBq	70.0 MBq
V-9	69.3 MBq	70.6 MBq	58.5 MBq
V-10	63.5 MBq	67.5 MBq	65.0 MBq
V-11	54.4 MBq	55.4 MBq	50.2 MBq
V-12	50.6 MBq	51.5 MBq	44.7 MBq
V-13	57.2 MBq	58.2 MBq	45.6 MBq
V-14	59.6 MBq	60.1 MBq	17.8 MBq
V-15	94.5 MBq	97.3 MBq	17.9 MBq
Total Activity	851 MBq	872 MBq	172.1 MBq

The values listed above are the computational results from section 4.0 along with the LHS derived results for the mean activity values and the LHS derived but analytically propagated standard deviations of the activity values.

The standard deviation of the total activity was calculated using the propagation of error formula such that

$$\begin{aligned}\sigma_{A(\text{Total})} = & (\sigma_{A(V-1)}^2 + \sigma_{A(V-2)}^2 + \sigma_{A(V-3)}^2 + \sigma_{A(V-4)}^2 \\ & + \sigma_{A(V-5)}^2 + \sigma_{A(V-6)}^2 + \sigma_{A(V-7)}^2 + \sigma_{A(V-8)}^2 \\ & + \sigma_{A(V-9)}^2 + \sigma_{A(V-10)}^2 + \sigma_{A(V-11)}^2 + \sigma_{A(V-12)}^2 \\ & + \sigma_{A(V-13)}^2 + \sigma_{A(V-14)}^2 + \sigma_{A(V-15)}^2)^{1/2}.\end{aligned}\quad (5-15)$$

Therefore the standard deviation for the total activity estimate is 172.1 MBq.

5.3 Accuracy of the Analysis

The accuracy, with a 95% confidence factor, of the 851 MBq total activity estimate can be derived from the 95% confidence value for a two-tail test (1.96) multiplied by the activity estimate standard deviation (172.1 MBq) quantity added to and subtracted from the mean activity estimate (Turner 1995). Subtracting 851 MBq from each of these numbers (1209.3 MBq and 534.7 MBq) and dividing by the same 851 MBq results in an analysis accuracy of + 42.1 % and - 37.2 %. If the MicroShield 4.2 computation is not used, and the analysis computation is based only on the LHS mean values, the accuracy of the analysis is ± 38.7 %.

6. CONCLUSION

The LHS technique used to evaluate the MicroShield 4.2 derived fluence rate estimation could also be used as a slightly more accurate method to estimate fluence rates. The LHS software is not limited to a specific set of source and shielding geometries. While the error introduced by the geometrical constraints of MicroShield 4.2 was minimal, the Crystal Ball 3.0 LHS method is not only more accurate but has the added bonus of a built-in sensitivity and uncertainty analysis. Either method could be used to calculate the fluence rate parameters needed — a matter of preference for the analyst.

Using MicroShield 4.2, the ventilation header is estimated to contain 851 MBq of ^{137}Cs ($^{137\text{m}}\text{Ba}$) activity with an analysis accuracy of + 42.1 % to - 37.2 % with a 95% confidence factor. The activity estimate using Crystal Ball 3.0 alone is 872 MBq $\pm$ 38.7 %. The sensitivity and uncertainty analyses not only provided the analysis accuracy estimate, but also helped to minimize the inaccuracies. Proper counting positions, shielding configurations, and calculational techniques were each determined in a manner to minimize uncertainty. While these techniques and associated accuracies were developed specifically for this application, they are readily adaptable to characterization of any fluid system or installed component.

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APPENDICES

A GammaVision 2.25 Operations

The counting performed was done with EG&G's Nomad Plus Multi-Channel Analyzer (MCA), an EG&G High Purity Germanium (HPGe) Detector, and EG&G's GammaVision 2.25 acquisition and analysis software. This portable spectrometry system was easily carried to the RDF's west roof each day. The system resolution can distinguish between photo-peaks of less than one keV difference in energy. It would be more than adequate to evaluate more complicated radio-nuclide spectrums than the ones evaluated in this project.

The GammaVision 2.25 software controls the detector and MCA during the counting process, and presents and analyzes the spectrum based on analyst calibrations and inputs. The analyst performs energy and efficiency calibrations, and after evaluating the spectrum, loads the nuclide library for the plausible nuclides present. The software will then, at the analysts direction, search the spectrum for valid peaks, analyze each peak, and present a peak analysis report. This report (see Figure A-1) automatically provides: (1) the peak energy range and centroid; (2) the nuclides each peak represents and their peak energy centroid; (3) the peak shape value of Full Width at Half of Maximum height (FWHM); the peaks gross and net count values; (4) the natural stochastic variability for the net counts based on the analyst selected confidence interval; and (5) the corresponding activity and its natural stochastic variability.

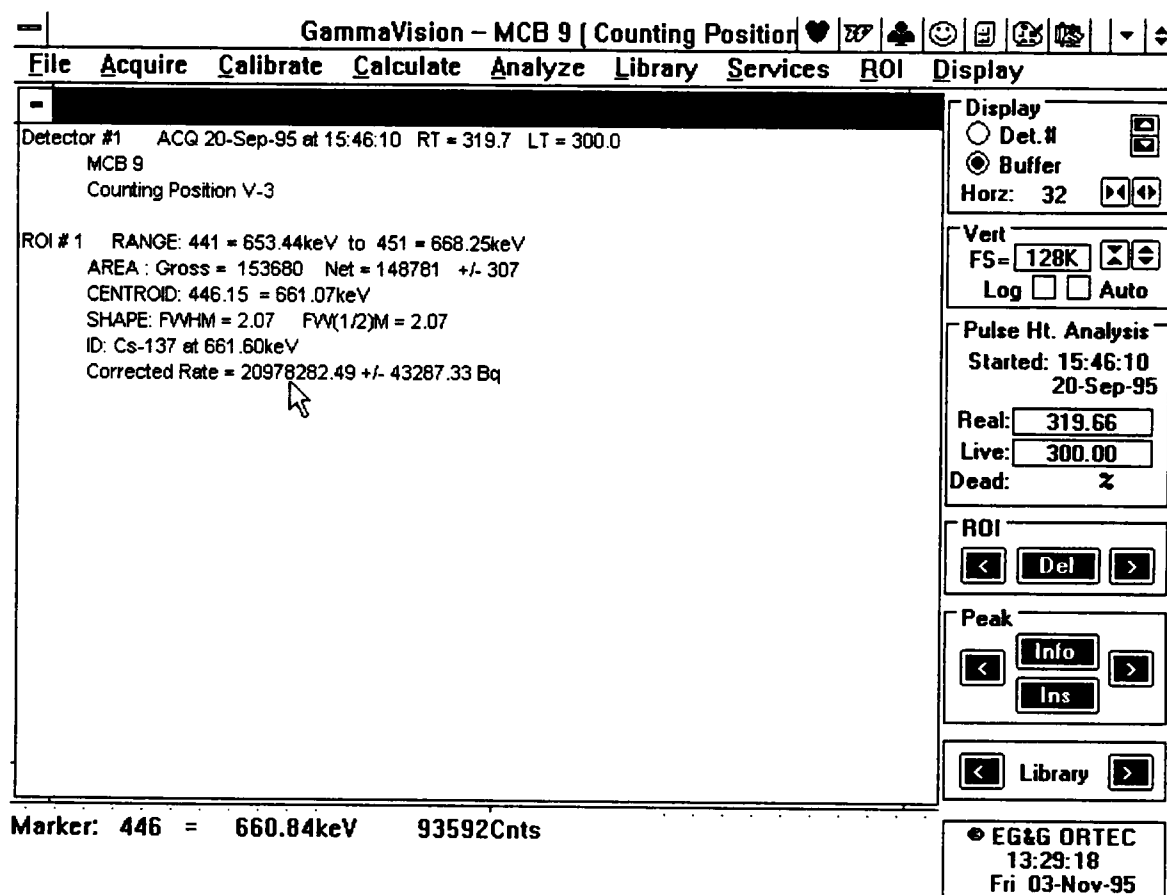


Figure A-1 — Region Of Interest (ROI) Report for Counting Position V-3. Above is an example of the analysis report supplied by the GammaVision 2.25 software. The analyst selects the plausible nuclides of interest from the spectrum, and loads an active library file containing these nuclides for the spectrum analysis. The analyst also performs an efficiency calibration with a NIST traceable source for the appropriate counting geometry. Based on these inputs, and the actual count performed, the software provides this report for each peak in the acquired spectrum.

This final activity estimation is calculated by the software based on the efficiency calibration efficiency factor, the total live-time of the count, and the library value for the corresponding nuclides photo-yield for the photon at the peak energy. These reports are self-contained for well defined counting geometries which can be duplicated with very little error during the efficiency calibration. Thus for a specific counting situation (or set of situations) for which the shielding and source distribution and distance can be accurately reproduced, GammaVision 2.25 provides the activity estimate for a spectrometry count.

Although these factors are not well defined in this application, the GammaVision 2.25 report was still useful as one of the inputs to the activity calculations. This value (A_p) is one of the primary inputs, along with the fluence rates calculated by either MicroShield 4.2 or Crystal Ball 3.0, to calculate the actual activity estimations. The energy and efficiency calibrations were performed with a NIST traceable ^{137}Cs point source at a distance of 48" (center-to-center).

Had the application involved multiple nuclides and/or multiple peaks, an efficiency curve could have been fitted from several point sources. This fit would involve additional errors for the uncertainty analysis however. Since preliminary spectroscopy results showed this to be a single nuclide/single peak application (see Figure A-2), a corresponding single point source efficiency calibration was chosen to minimize the

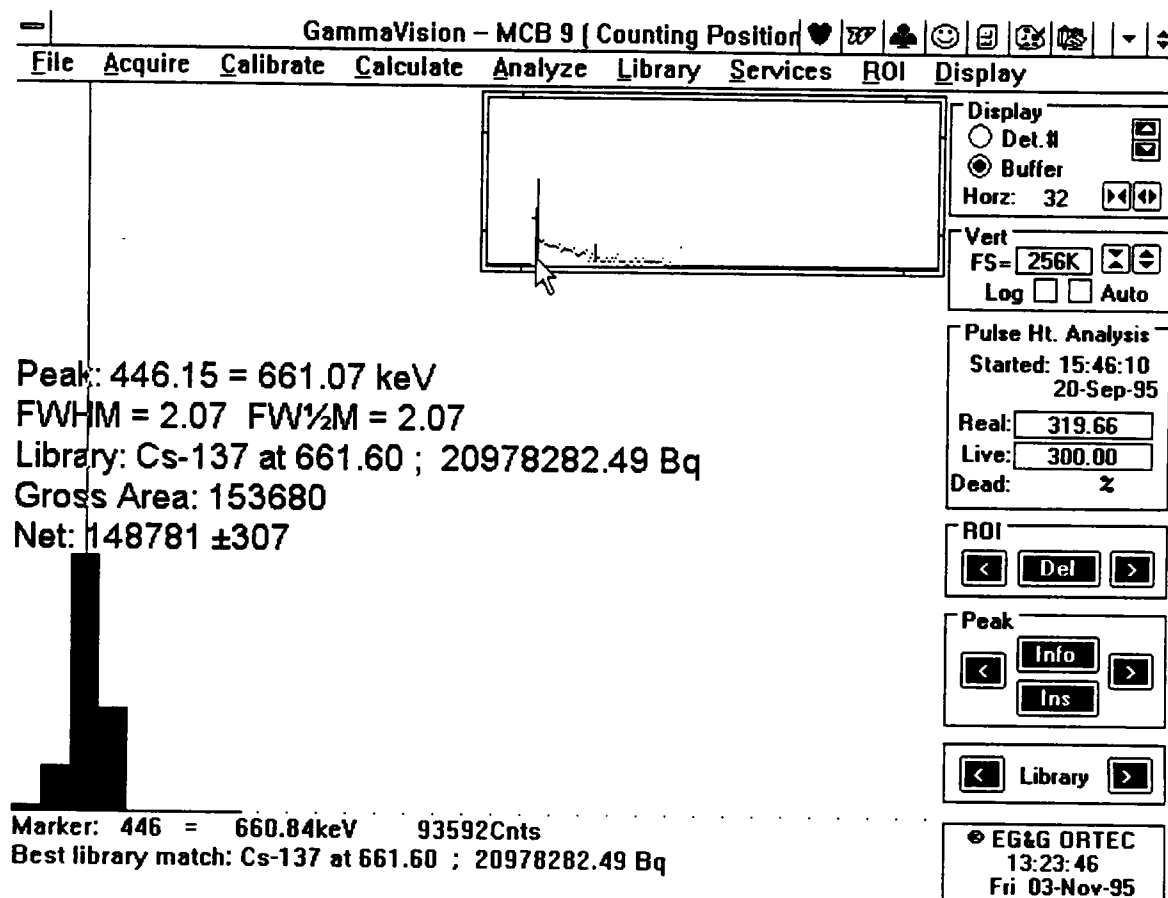


Figure A-2 — GammaVision 2.25 Spectrum For Counting Position V-3. The gamma photon spectrum shown above is focused on the 661.6 keV ^{137}Cs ($^{137\text{m}}\text{Ba}$) photo-peak. Note the small arrow pointing to the same photo-peak in the small box in the upper right corner. This shows the position of the peak relative to the broad-range gamma spectrum. The only other photo-peak on the entire spectrum is the 1.44 MeV peak for naturally occurring ^{40}K . This can be seen as the very small photo-peak to the right of the arrow on the broad-range gamma spectrum.

analysis uncertainty. This and a twelve-hour live-time efficiency count ensured that the uncertainty for the calibrated efficiency for the A_p value was negligible.

B MicroShield 4.2 Calculations

MicroShield 4.2 was used to calculate the 661.6 keV photon fluence rates at the detector center based on several counting geometries. This software provides dose, fluence, and energy fluence calculation results using a point-kernel method for many common source and shielding geometries. It is very flexible and easy to apply to counting geometries. Although it calculates and displays values with and without build-up, only calculations without build-up are of use in spectrometry applications.

This software was also used to perform sensitivity analyses on the magnitude of error introduced by variations in source distribution and shielding parameters. These sensitivity results were used to develop the counting procedure, shielding configuration, and counting distance. They were also used to determine the source distribution model which would introduce the least amount of error given plausible variations in the model parameters. The fluence-rate calculation report provided by MicroShield 4.2 for an example distribution of this model (the one-inch deep, one-foot wide, nine-foot long uniformly distributed slab source) is shown on the next two pages. The activity used to calibrate this model is the constant A_{CAL} value of .37 Mbq of $^{137}\text{Cs}(^{137m}\text{Ba})$ corrected for gamma-yield.

MicroShield 4.21 - Serial #4.21-00980
Lockheed Martin Energy Systems

Page : 1
DOS File: V4S9D1C.MS4
Run Date: October 13, 1995
Run Time: 3:39 p.m. Friday
Duration: 0:00:31

File Ref: _____
Date: ____/____/____
By: _____
Checked: _____

Case Title: Slab source centered in vent duct (1 in x 12 in x 108 in)

GEOMETRY 13 - Rectangular Volume

	centimeters	feet	and inches
Dose point coordinate X:	124.714	4.0	1.1
Dose point coordinate Y:	137.16	4.0	6.0
Dose point coordinate Z:	0.0	0.0	.0
Rectangular volume width :	30.48	1.0	.0
Rectangular volume length:	2.54	0.0	1.0
Rectangular volume height:	274.32	9.0	.0
Shield 1:	0.254	0.0	.1
Air Gap:	121.92	4.0	.0

Source Volume: 21237.6 cm³ .75 cu ft. 1296. cu in.

Material	MATERIAL DENSITIES (g/cm ³)		
	Source Shield	Shield 1 Slab	Air Gap
Air			0.00122
Iron	7.86		

BUILDUP

Method: Buildup Factor Tables
The material reference is Shield 1

INTEGRATION PARAMETERS

	Quadrature Order
X Direction	20
Y Direction	40
Z Direction	40

SOURCE WAS ENTERED AS ENERGIES ONLY

===== RESULTS =====

Energy (MeV)	Activity (photons/sec)	Energy Fluence Rate (MeV/sq cm/sec)		Exposure Rate In Air (mR/hr)	
		No Buildup	With Buildup	No Buildup	With Buildup
0.6616	3.145e+005	5.662e-001	7.348e-001	1.098e-003	1.424e-003
TOTAL:	3.145e+005	5.662e-001	7.348e-001	1.098e-003	1.424e-003

MicroShield 4.21 - Serial #4.21-00980
 Licensed to Lockheed Martin Energy Systems
 RESULTS WITHOUT BUILDUP
 FILE: V4S9D1C.MS4

Case Title: Slab source centered in vent duct (1 in x 12 in x 108 in)
 This case was run on Friday, October 13, 1995 at 3:39 p.m.

Group #	Energy (MeV)	Activity photons/sec	<--- RESULTS AT THE DOSE POINT - NO BUILDUP --->		
			Fluence Rate photons/cm ² /sec	Energy Fluence Rate MeV/cm ² /sec	Exposure Rate mR/hr
1	.662	3.145e+005	8.558e-001	5.662e-001	1.098e-003
TOTALS:		3.145e+005	8.558e-001	5.662e-001	1.098e-003

C Crystal Ball 3.0 Calculations

Crystal Ball 3.0 is a forecasting application software designed primarily for financial and risk analysis. It is a very easy to use Monte Carlo program which is run in conjunction with either of two popularly used spreadsheet software packages. It can be used for stratified (LHS) or normal Monte Carlo simulations, and has an internal sensitivity analysis function which operates on a rank correlation method.

Crystal Ball 3.0 was used for three separate purposes during this project: (1) uncertainty analysis, (2) sensitivity analysis, and (3) a point-kernel method for calculating photon fluence rates. The uncertainty analysis for the fluence rates applicable to each counting configuration was run based on the assumptions outlined in section 5.1. An example of the spreadsheet used to analyze the standard configuration fluence rates is shown in Figure C-1, and the resultant report is on the remaining pages of this appendix. The sensitivity analysis can be automatically generated from the Monte Carlo run for uncertainty. This can be reported as a rank correlation factor for each assumption, or a relative percentage (normalized to 100 %) of the rank correlation for each function.

An unforeseen application of this software was its use to generate the fluence-rate values. The mean values for the fluence rates calculated during the uncertainty analysis are more specifically representative than the values generated by the shielding software.

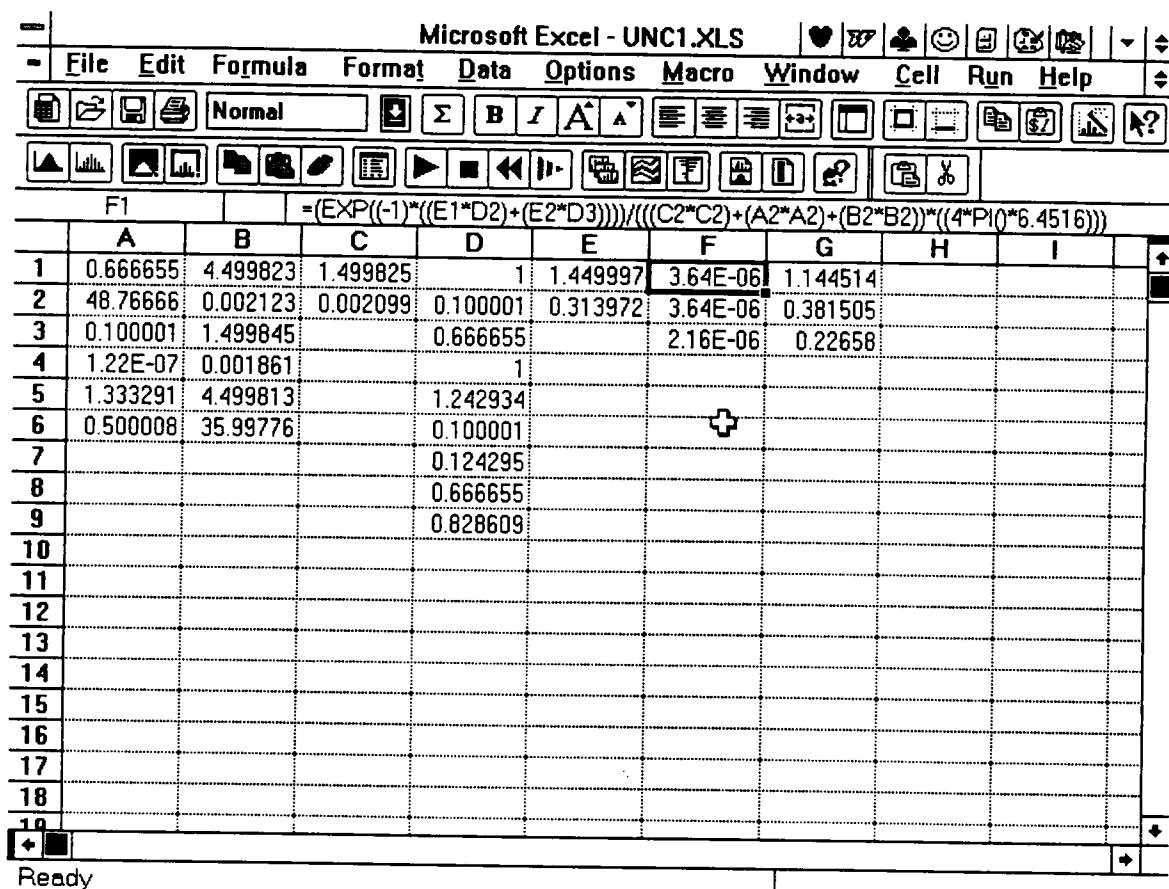
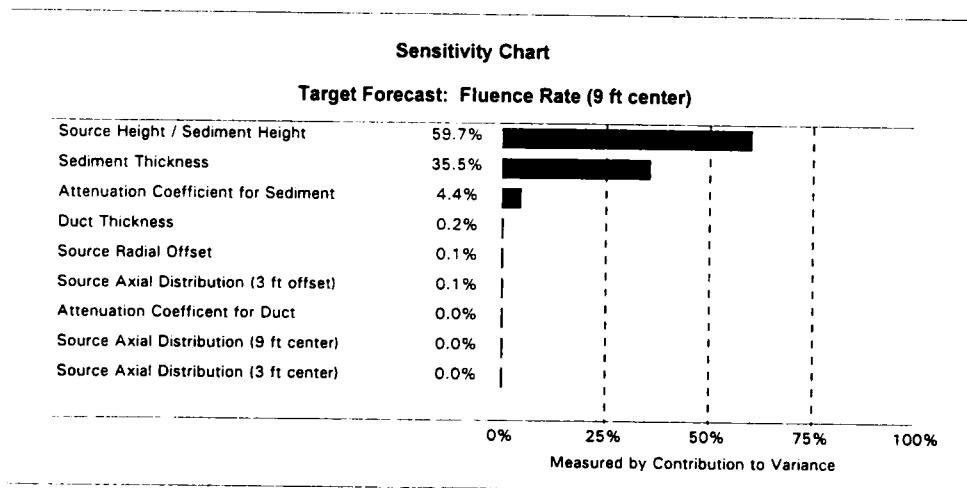


Figure C-1 — Spreadsheet of Standard Configuration Fluence Rate Model in Crystal Ball 3.0. Above is an example of the spread sheet used to define assumption and forecast cells for the uncertainty and sensitivity analysis of the standard configuration fluence rates. The assumptions and forecasts which are listed in each cell are described in the report on the following pages.

Crystal Ball Report
Simulation started on 11/8/95 at 8:41:34
Simulation stopped on 11/8/95 at 8:53:41



Forecast: Fluence Rate (3 ft center)

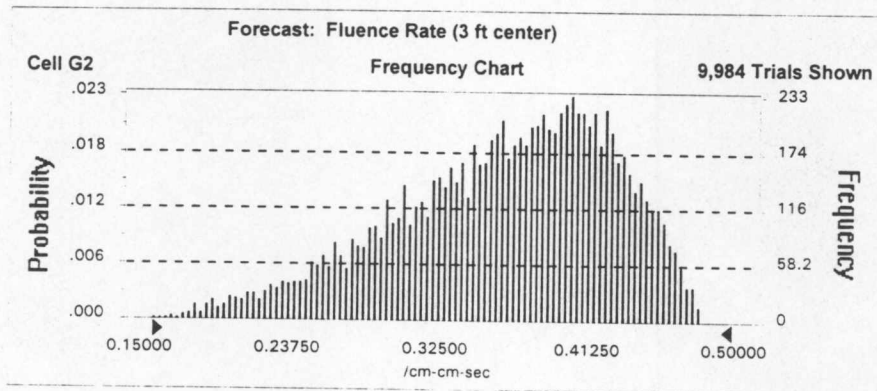
Cell: G2

Summary:

Display Range is from 0.15000 to 0.50000 /cm-cm-sec
Entire Range is from 0.11744 to 0.48267 /cm-cm-sec
After 10,000 Trials, the Std. Error of the Mean is 0.00067

Statistics:

	Value
Trials	10000
Mean	0.36192
Median	0.37161
Mode	---
Standard Deviation	0.06671
Variance	0.00445
Skewness	-0.59484
Kurtosis	2.83167
Coeff. of Variability	0.18432
Range Minimum	0.11744
Range Maximum	0.48267
Range Width	0.36523
Mean Std. Error	0.00067



Forecast: Fluence Rate (3 ft center) (cont'd)

Cell: G2

Percentiles:

<u>Percentile</u>	<u>/cm-cm-sec</u>
0.0%	0.11744
2.5%	0.21185
5.0%	0.23720
50.0%	0.37161
95.0%	0.45498
97.5%	0.46361
100.0%	0.48267

Frequency Counts:

Frequency:

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
	-Infinity	0.15000	0.001600	16
1	0.15000	0.15350	0.000200	2
2	0.15350	0.15700	0.000300	3
3	0.15700	0.16050	0.000300	3
4	0.16050	0.16400	0.000400	4
5	0.16400	0.16750	0.000300	3
6	0.16750	0.17100	0.000600	6
7	0.17100	0.17450	0.000800	8
8	0.17450	0.17800	0.001700	17
9	0.17800	0.18150	0.000700	7
10	0.18150	0.18500	0.001700	17
11	0.18500	0.18850	0.002200	22
12	0.18850	0.19200	0.001200	12
13	0.19200	0.19550	0.001700	17
14	0.19550	0.19900	0.002500	25
15	0.19900	0.20250	0.002300	23
16	0.20250	0.20600	0.002100	21
17	0.20600	0.20950	0.002800	28
18	0.20950	0.21300	0.002800	28
19	0.21300	0.21650	0.002100	21
20	0.21650	0.22000	0.002900	29
21	0.22000	0.22350	0.003700	37
22	0.22350	0.22700	0.003400	34
23	0.22700	0.23050	0.004000	40
24	0.23050	0.23400	0.003800	38
25	0.23400	0.23750	0.004000	40
26	0.23750	0.24100	0.004000	40
27	0.24100	0.24450	0.004200	42
28	0.24450	0.24800	0.006100	61

Forecast: Fluence Rate (3 ft center) (cont'd)

Cell: G2

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
29	0.24800	0.25150	0.005700	57
30	0.25150	0.25500	0.006700	67
31	0.25500	0.25850	0.005600	56
32	0.25850	0.26200	0.008000	80
33	0.26200	0.26550	0.006700	67
34	0.26550	0.26900	0.005400	54
35	0.26900	0.27250	0.008400	84
36	0.27250	0.27600	0.007800	78
37	0.27600	0.27950	0.007500	75
38	0.27950	0.28300	0.009600	96
39	0.28300	0.28650	0.009800	98
40	0.28650	0.29000	0.008600	86
41	0.29000	0.29350	0.012500	125
42	0.29350	0.29700	0.010200	102
43	0.29700	0.30050	0.010700	107
44	0.30050	0.30400	0.014000	140
45	0.30400	0.30750	0.010000	100
46	0.30750	0.31100	0.011900	119
47	0.31100	0.31450	0.012400	124
48	0.31450	0.31800	0.010800	108
49	0.31800	0.32150	0.014500	145
50	0.32150	0.32500	0.014900	149
51	0.32500	0.32850	0.013900	139
52	0.32850	0.33200	0.015900	159
53	0.33200	0.33550	0.014300	143
54	0.33550	0.33900	0.016400	164
55	0.33900	0.34250	0.012900	129
56	0.34250	0.34600	0.018200	182
57	0.34600	0.34950	0.016200	162
58	0.34950	0.35300	0.016400	164
59	0.35300	0.35650	0.018800	188
60	0.35650	0.36000	0.019500	195
61	0.36000	0.36350	0.020900	209
62	0.36350	0.36700	0.016900	169
63	0.36700	0.37050	0.018300	183
64	0.37050	0.37400	0.019100	191
65	0.37400	0.37750	0.018300	183
66	0.37750	0.38100	0.020100	201
67	0.38100	0.38450	0.020400	204
68	0.38450	0.38800	0.021500	215
69	0.38800	0.39150	0.020000	200
70	0.39150	0.39500	0.019600	196

Forecast: Fluence Rate (3 ft center) (cont'd)

Cell: G2

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
71	0.39500	0.39850	0.021700	217
72	0.39850	0.40200	0.022500	225
73	0.40200	0.40550	0.023300	233
74	0.40550	0.40900	0.021600	216
75	0.40900	0.41250	0.021600	216
76	0.41250	0.41600	0.020400	204
77	0.41600	0.41950	0.021600	216
78	0.41950	0.42300	0.018200	182
79	0.42300	0.42650	0.022100	221
80	0.42650	0.43000	0.019600	196
81	0.43000	0.43350	0.016600	166
82	0.43350	0.43700	0.017200	172
83	0.43700	0.44050	0.015400	154
84	0.44050	0.44400	0.013600	136
85	0.44400	0.44750	0.014500	145
86	0.44750	0.45100	0.012600	126
87	0.45100	0.45450	0.011700	117
88	0.45450	0.45800	0.011700	117
89	0.45800	0.46150	0.010300	103
90	0.46150	0.46500	0.008000	80
91	0.46500	0.46850	0.007400	74
92	0.46850	0.47200	0.005700	57
93	0.47200	0.47550	0.003700	37
94	0.47550	0.47900	0.003600	36
95	0.47900	0.48250	0.001600	16
96	0.48250	0.48600	0.000100	1
97	0.48600	0.48950	0.000000	0
98	0.48950	0.49300	0.000000	0
99	0.49300	0.49650	0.000000	0
100	0.49650	0.50000	0.000000	0
	0.50000	+ Infinity	0.000000	0
Total:			1.000000	10000

Cumulative:

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
	-Infinity	0.15000	0.001600	16
1	0.15000	0.15350	0.001800	18
2	0.15350	0.15700	0.002100	21
3	0.15700	0.16050	0.002400	24
4	0.16050	0.16400	0.002800	28
5	0.16400	0.16750	0.003100	31
6	0.16750	0.17100	0.003700	37

Forecast: Fluence Rate (3 ft center) (cont'd)

Cell: G2

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
7	0.17100	0.17450	0.004500	45
8	0.17450	0.17800	0.006200	62
9	0.17800	0.18150	0.006900	69
10	0.18150	0.18500	0.008600	86
11	0.18500	0.18850	0.010800	108
12	0.18850	0.19200	0.012000	120
13	0.19200	0.19550	0.013700	137
14	0.19550	0.19900	0.016200	162
15	0.19900	0.20250	0.018500	185
16	0.20250	0.20600	0.020600	206
17	0.20600	0.20950	0.023400	234
18	0.20950	0.21300	0.026200	262
19	0.21300	0.21650	0.028300	283
20	0.21650	0.22000	0.031200	312
21	0.22000	0.22350	0.034900	349
22	0.22350	0.22700	0.038300	383
23	0.22700	0.23050	0.042300	423
24	0.23050	0.23400	0.046100	461
25	0.23400	0.23750	0.050100	501
26	0.23750	0.24100	0.054100	541
27	0.24100	0.24450	0.058300	583
28	0.24450	0.24800	0.064400	644
29	0.24800	0.25150	0.070100	701
30	0.25150	0.25500	0.076800	768
31	0.25500	0.25850	0.082400	824
32	0.25850	0.26200	0.090400	904
33	0.26200	0.26550	0.097100	971
34	0.26550	0.26900	0.102500	1025
35	0.26900	0.27250	0.110900	1109
36	0.27250	0.27600	0.118700	1187
37	0.27600	0.27950	0.126200	1262
38	0.27950	0.28300	0.135800	1358
39	0.28300	0.28650	0.145600	1456
40	0.28650	0.29000	0.154200	1542
41	0.29000	0.29350	0.166700	1667
42	0.29350	0.29700	0.176900	1769
43	0.29700	0.30050	0.187600	1876
44	0.30050	0.30400	0.201600	2016
45	0.30400	0.30750	0.211600	2116
46	0.30750	0.31100	0.223500	2235
47	0.31100	0.31450	0.235900	2359
48	0.31450	0.31800	0.246700	2467

Forecast: Fluence Rate (3 ft center) (cont'd)

Cell: G2

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
49	0.31800	0.32150	0.261200	2612
50	0.32150	0.32500	0.276100	2761
51	0.32500	0.32850	0.290000	2900
52	0.32850	0.33200	0.305900	3059
53	0.33200	0.33550	0.320200	3202
54	0.33550	0.33900	0.336600	3366
55	0.33900	0.34250	0.349500	3495
56	0.34250	0.34600	0.367700	3677
57	0.34600	0.34950	0.383900	3839
58	0.34950	0.35300	0.400300	4003
59	0.35300	0.35650	0.419100	4191
60	0.35650	0.36000	0.438600	4386
61	0.36000	0.36350	0.459500	4595
62	0.36350	0.36700	0.476400	4764
63	0.36700	0.37050	0.494700	4947
64	0.37050	0.37400	0.513800	5138
65	0.37400	0.37750	0.532100	5321
66	0.37750	0.38100	0.552200	5522
67	0.38100	0.38450	0.572600	5726
68	0.38450	0.38800	0.594100	5941
69	0.38800	0.39150	0.614100	6141
70	0.39150	0.39500	0.633700	6337
71	0.39500	0.39850	0.655400	6554
72	0.39850	0.40200	0.677900	6779
73	0.40200	0.40550	0.701200	7012
74	0.40550	0.40900	0.722800	7228
75	0.40900	0.41250	0.744400	7444
76	0.41250	0.41600	0.764800	7648
77	0.41600	0.41950	0.786400	7864
78	0.41950	0.42300	0.804600	8046
79	0.42300	0.42650	0.826700	8267
80	0.42650	0.43000	0.846300	8463
81	0.43000	0.43350	0.862900	8629
82	0.43350	0.43700	0.880100	8801
83	0.43700	0.44050	0.895500	8955
84	0.44050	0.44400	0.909100	9091
85	0.44400	0.44750	0.923600	9236
86	0.44750	0.45100	0.936200	9362
87	0.45100	0.45450	0.947900	9479
88	0.45450	0.45800	0.959600	9596
89	0.45800	0.46150	0.969900	9699
90	0.46150	0.46500	0.977900	9779

Forecast: Fluence Rate (3 ft center) (cont'd)

Cell: G2

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
91	0.46500	0.46850	0.985300	9853
92	0.46850	0.47200	0.991000	9910
93	0.47200	0.47550	0.994700	9947
94	0.47550	0.47900	0.998300	9983
95	0.47900	0.48250	0.999900	9999
96	0.48250	0.48600	1.000000	10000
97	0.48600	0.48950	1.000000	10000
98	0.48950	0.49300	1.000000	10000
99	0.49300	0.49650	1.000000	10000
100	0.49650	0.50000	1.000000	10000
	0.50000	+ Infinity	1.000000	10000

End of Forecast

Forecast: Fluence Rate (9 ft center)

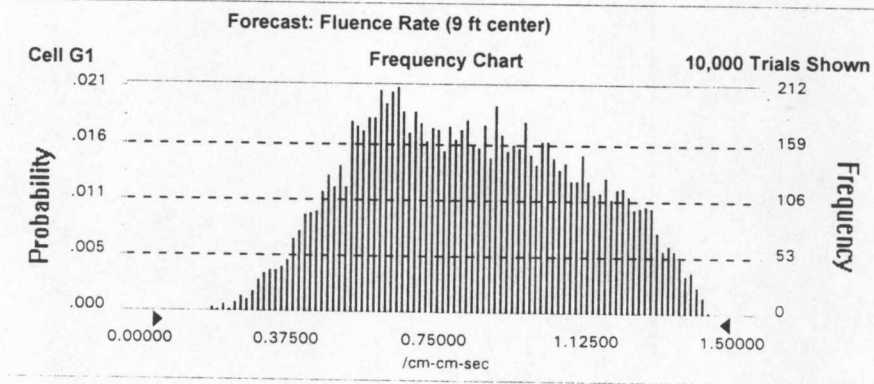
Cell: G1

Summary:

Display Range is from 0.00000 to 1.50000 /cm-cm-sec
 Entire Range is from 0.13055 to 1.46160 /cm-cm-sec
 After 10,000 Trials, the Std. Error of the Mean is 0.00280

Statistics:

	Value
Trials	10000
Mean	0.82709
Median	0.81238
Mode	---
Standard Deviation	0.27958
Variance	0.07816
Skewness	0.11871
Kurtosis	2.12291
Coeff. of Variability	0.33803
Range Minimum	0.13055
Range Maximum	1.46160
Range Width	1.33105
Mean Std. Error	0.00280



Forecast: Fluence Rate (9 ft center) (cont'd)

Cell: G1

Percentiles:

<u>Percentile</u>	<u>/cm-cm-sec</u>
0.0%	0.13055
2.5%	0.34051
5.0%	0.39856
50.0%	0.81238
95.0%	1.29475
97.5%	1.34659
100.0%	1.46160

Frequency Counts:

Frequency:

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
	-Infinity	0.00000	0.000000	0
1	0.00000	0.01500	0.000000	0
2	0.01500	0.03000	0.000000	0
3	0.03000	0.04500	0.000000	0
4	0.04500	0.06000	0.000000	0
5	0.06000	0.07500	0.000000	0
6	0.07500	0.09000	0.000000	0
7	0.09000	0.10500	0.000000	0
8	0.10500	0.12000	0.000000	0
9	0.12000	0.13500	0.000100	1
10	0.13500	0.15000	0.000100	1
11	0.15000	0.16500	0.000400	4
12	0.16500	0.18000	0.000200	2
13	0.18000	0.19500	0.000700	7
14	0.19500	0.21000	0.000200	2
15	0.21000	0.22500	0.000800	8
16	0.22500	0.24000	0.001400	14
17	0.24000	0.25500	0.001100	11
18	0.25500	0.27000	0.002000	20
19	0.27000	0.28500	0.003000	30
20	0.28500	0.30000	0.003600	36
21	0.30000	0.31500	0.003900	39
22	0.31500	0.33000	0.004000	40
23	0.33000	0.34500	0.004200	42
24	0.34500	0.36000	0.004800	48
25	0.36000	0.37500	0.006900	69
26	0.37500	0.39000	0.007600	76
27	0.39000	0.40500	0.009200	92
28	0.40500	0.42000	0.009400	94

Forecast: Fluence Rate (9 ft center) (cont'd)

Cell: G1

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
29	0.42000	0.43500	0.009500	95
30	0.43500	0.45000	0.011300	113
31	0.45000	0.46500	0.012900	129
32	0.46500	0.48000	0.011900	119
33	0.48000	0.49500	0.013900	139
34	0.49500	0.51000	0.011800	118
35	0.51000	0.52500	0.018000	180
36	0.52500	0.54000	0.017500	175
37	0.54000	0.55500	0.017100	171
38	0.55500	0.57000	0.018400	184
39	0.57000	0.58500	0.018400	184
40	0.58500	0.60000	0.021000	210
41	0.60000	0.61500	0.019700	197
42	0.61500	0.63000	0.020800	208
43	0.63000	0.64500	0.021200	212
44	0.64500	0.66000	0.019000	190
45	0.66000	0.67500	0.016900	169
46	0.67500	0.69000	0.019000	190
47	0.69000	0.70500	0.017800	178
48	0.70500	0.72000	0.016100	161
49	0.72000	0.73500	0.017400	174
50	0.73500	0.75000	0.017300	173
51	0.75000	0.76500	0.015200	152
52	0.76500	0.78000	0.017600	176
53	0.78000	0.79500	0.016400	164
54	0.79500	0.81000	0.017300	173
55	0.81000	0.82500	0.018200	182
56	0.82500	0.84000	0.015900	159
57	0.84000	0.85500	0.015600	156
58	0.85500	0.87000	0.017700	177
59	0.87000	0.88500	0.014700	147
60	0.88500	0.90000	0.019600	196
61	0.90000	0.91500	0.016800	168
62	0.91500	0.93000	0.015200	152
63	0.93000	0.94500	0.015800	158
64	0.94500	0.96000	0.015500	155
65	0.96000	0.97500	0.018000	180
66	0.97500	0.99000	0.015000	150
67	0.99000	1.00500	0.014000	140
68	1.00500	1.02000	0.016100	161
69	1.02000	1.03500	0.016100	161
70	1.03500	1.05000	0.014600	146

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
71	1.05000	1.06500	0.013500	135
72	1.06500	1.08000	0.014200	142
73	1.08000	1.09500	0.012500	125
74	1.09500	1.11000	0.012500	125
75	1.11000	1.12500	0.014900	149
76	1.12500	1.14000	0.012500	125
77	1.14000	1.15500	0.011200	112
78	1.15500	1.17000	0.011400	114
79	1.17000	1.18500	0.012700	127
80	1.18500	1.20000	0.010800	108
81	1.20000	1.21500	0.011700	117
82	1.21500	1.23000	0.011900	119
83	1.23000	1.24500	0.011000	110
84	1.24500	1.26000	0.009800	98
85	1.26000	1.27500	0.010000	100
86	1.27500	1.29000	0.010200	102
87	1.29000	1.30500	0.010000	100
88	1.30500	1.32000	0.007700	77
89	1.32000	1.33500	0.005900	59
90	1.33500	1.35000	0.006400	64
91	1.35000	1.36500	0.006000	60
92	1.36500	1.38000	0.005200	52
93	1.38000	1.39500	0.003700	37
94	1.39500	1.41000	0.004000	40
95	1.41000	1.42500	0.002500	25
96	1.42500	1.44000	0.001600	16
97	1.44000	1.45500	0.000300	3
98	1.45500	1.47000	0.000100	1
99	1.47000	1.48500	0.000000	0
100	1.48500	1.50000	0.000000	0
	1.50000	+Infinity	0.000000	0
Total:			1.000000	10000

Cumulative:

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
	-Infinity	0.00000	0.000000	0
1	0.00000	0.01500	0.000000	0
2	0.01500	0.03000	0.000000	0
3	0.03000	0.04500	0.000000	0
4	0.04500	0.06000	0.000000	0
5	0.06000	0.07500	0.000000	0
6	0.07500	0.09000	0.000000	0

Forecast: Fluence Rate (9 ft center) (cont'd)

Cell: G1

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
7	0.09000	0.10500	0.000000	0
8	0.10500	0.12000	0.000000	0
9	0.12000	0.13500	0.000100	1
10	0.13500	0.15000	0.000200	2
11	0.15000	0.16500	0.000600	6
12	0.16500	0.18000	0.000800	8
13	0.18000	0.19500	0.001500	15
14	0.19500	0.21000	0.001700	17
15	0.21000	0.22500	0.002500	25
16	0.22500	0.24000	0.003900	39
17	0.24000	0.25500	0.005000	50
18	0.25500	0.27000	0.007000	70
19	0.27000	0.28500	0.010000	100
20	0.28500	0.30000	0.013600	136
21	0.30000	0.31500	0.017500	175
22	0.31500	0.33000	0.021500	215
23	0.33000	0.34500	0.025700	257
24	0.34500	0.36000	0.030500	305
25	0.36000	0.37500	0.037400	374
26	0.37500	0.39000	0.045000	450
27	0.39000	0.40500	0.054200	542
28	0.40500	0.42000	0.063600	636
29	0.42000	0.43500	0.073100	731
30	0.43500	0.45000	0.084400	844
31	0.45000	0.46500	0.097300	973
32	0.46500	0.48000	0.109200	1092
33	0.48000	0.49500	0.123100	1231
34	0.49500	0.51000	0.134900	1349
35	0.51000	0.52500	0.152900	1529
36	0.52500	0.54000	0.170400	1704
37	0.54000	0.55500	0.187500	1875
38	0.55500	0.57000	0.205900	2059
39	0.57000	0.58500	0.224300	2243
40	0.58500	0.60000	0.245300	2453
41	0.60000	0.61500	0.265000	2650
42	0.61500	0.63000	0.285800	2858
43	0.63000	0.64500	0.307000	3070
44	0.64500	0.66000	0.326000	3260
45	0.66000	0.67500	0.342900	3429
46	0.67500	0.69000	0.361900	3619
47	0.69000	0.70500	0.379700	3797
48	0.70500	0.72000	0.395800	3958

Forecast: Fluence Rate (9 ft center) (cont'd)

Cell: G1

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
49	0.72000	0.73500	0.413200	4132
50	0.73500	0.75000	0.430500	4305
51	0.75000	0.76500	0.445700	4457
52	0.76500	0.78000	0.463300	4633
53	0.78000	0.79500	0.479700	4797
54	0.79500	0.81000	0.497000	4970
55	0.81000	0.82500	0.515200	5152
56	0.82500	0.84000	0.531100	5311
57	0.84000	0.85500	0.546700	5467
58	0.85500	0.87000	0.564400	5644
59	0.87000	0.88500	0.579100	5791
60	0.88500	0.90000	0.598700	5987
61	0.90000	0.91500	0.615500	6155
62	0.91500	0.93000	0.630700	6307
63	0.93000	0.94500	0.646500	6465
64	0.94500	0.96000	0.662000	6620
65	0.96000	0.97500	0.680000	6800
66	0.97500	0.99000	0.695000	6950
67	0.99000	1.00500	0.709000	7090
68	1.00500	1.02000	0.725100	7251
69	1.02000	1.03500	0.741200	7412
70	1.03500	1.05000	0.755800	7558
71	1.05000	1.06500	0.769300	7693
72	1.06500	1.08000	0.783500	7835
73	1.08000	1.09500	0.796000	7960
74	1.09500	1.11000	0.808500	8085
75	1.11000	1.12500	0.823400	8234
76	1.12500	1.14000	0.835900	8359
77	1.14000	1.15500	0.847100	8471
78	1.15500	1.17000	0.858500	8585
79	1.17000	1.18500	0.871200	8712
80	1.18500	1.20000	0.882000	8820
81	1.20000	1.21500	0.893700	8937
82	1.21500	1.23000	0.905600	9056
83	1.23000	1.24500	0.916600	9166
84	1.24500	1.26000	0.926400	9264
85	1.26000	1.27500	0.936400	9364
86	1.27500	1.29000	0.946600	9466
87	1.29000	1.30500	0.956600	9566
88	1.30500	1.32000	0.964300	9643
89	1.32000	1.33500	0.970200	9702
90	1.33500	1.35000	0.976600	9766

Forecast: Fluence Rate (9 ft center) (cont'd)

Cell: G1

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
91	1.35000	1.36500	0.982600	9826
92	1.36500	1.38000	0.987800	9878
93	1.38000	1.39500	0.991500	9915
94	1.39500	1.41000	0.995500	9955
95	1.41000	1.42500	0.998000	9980
96	1.42500	1.44000	0.999600	9996
97	1.44000	1.45500	0.999900	9999
98	1.45500	1.47000	1.000000	10000
99	1.47000	1.48500	1.000000	10000
100	1.48500	1.50000	1.000000	10000
	1.50000	+ Infinity	1.000000	10000

End of Forecast

Forecast: Fluence Rate (3 ft offset)

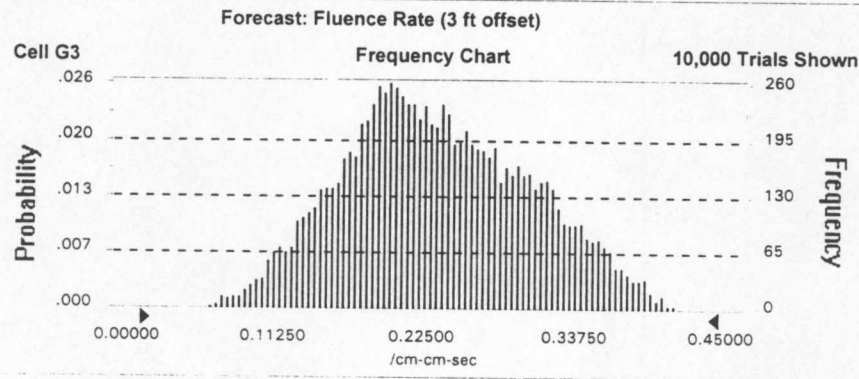
Cell: G3

Summary:

Display Range is from 0.00000 to 0.45000 /cm-cm-sec
 Entire Range is from 0.04214 to 0.41825 /cm-cm-sec
 After 10,000 Trials, the Std. Error of the Mean is 0.00071

Statistics:

	<u>Value</u>
Trials	10000
Mean	0.23246
Median	0.22704
Mode	---
Standard Deviation	0.07144
Variance	0.00510
Skewness	0.16141
Kurtosis	2.40380
Coeff. of Variability	0.30731
Range Minimum	0.04214
Range Maximum	0.41825
Range Width	0.37610
Mean Std. Error	0.00071



Forecast: Fluence Rate (3 ft offset) (cont'd)

Cell: G3

Percentiles:

<u>Percentile</u>	<u>/cm-cm-sec</u>
0.0%	0.04214
2.5%	0.10408
5.0%	0.12063
50.0%	0.22704
95.0%	0.35625
97.5%	0.37297
100.0%	0.41825

Frequency Counts:

Frequency:

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
	-Infinity	0.00000	0.000000	0
1	0.00000	0.00450	0.000000	0
2	0.00450	0.00900	0.000000	0
3	0.00900	0.01350	0.000000	0
4	0.01350	0.01800	0.000000	0
5	0.01800	0.02250	0.000000	0
6	0.02250	0.02700	0.000000	0
7	0.02700	0.03150	0.000000	0
8	0.03150	0.03600	0.000000	0
9	0.03600	0.04050	0.000000	0
10	0.04050	0.04500	0.000100	1
11	0.04500	0.04950	0.000100	1
12	0.04950	0.05400	0.000100	1
13	0.05400	0.05850	0.000300	3
14	0.05850	0.06300	0.000500	5
15	0.06300	0.06750	0.001400	14
16	0.06750	0.07200	0.001200	12
17	0.07200	0.07650	0.001500	15
18	0.07650	0.08100	0.001500	15
19	0.08100	0.08550	0.002100	21
20	0.08550	0.09000	0.002800	28
21	0.09000	0.09450	0.003300	33
22	0.09450	0.09900	0.003600	36
23	0.09900	0.10350	0.005600	56
24	0.10350	0.10800	0.006500	65
25	0.10800	0.11250	0.007100	71
26	0.11250	0.11700	0.006500	65
27	0.11700	0.12150	0.007200	72
28	0.12150	0.12600	0.010100	101

Forecast: Fluence Rate (3 ft offset) (cont'd)

Cell: G3

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
29	0.12600	0.13050	0.010500	105
30	0.13050	0.13500	0.011100	111
31	0.13500	0.13950	0.011600	116
32	0.13950	0.14400	0.013700	137
33	0.14400	0.14850	0.013900	139
34	0.14850	0.15300	0.013900	139
35	0.15300	0.15750	0.014600	146
36	0.15750	0.16200	0.017300	173
37	0.16200	0.16650	0.018100	181
38	0.16650	0.17100	0.017500	175
39	0.17100	0.17550	0.021300	213
40	0.17550	0.18000	0.021700	217
41	0.18000	0.18450	0.023700	237
42	0.18450	0.18900	0.025800	258
43	0.18900	0.19350	0.025000	250
44	0.19350	0.19800	0.026000	260
45	0.19800	0.20250	0.025500	255
46	0.20250	0.20700	0.024500	245
47	0.20700	0.21150	0.023700	237
48	0.21150	0.21600	0.023700	237
49	0.21600	0.22050	0.021900	219
50	0.22050	0.22500	0.023500	235
51	0.22500	0.22950	0.021300	213
52	0.22950	0.23400	0.021000	210
53	0.23400	0.23850	0.023700	237
54	0.23850	0.24300	0.022500	225
55	0.24300	0.24750	0.019000	190
56	0.24750	0.25200	0.019200	192
57	0.25200	0.25650	0.020600	206
58	0.25650	0.26100	0.019100	191
59	0.26100	0.26550	0.018500	185
60	0.26550	0.27000	0.018400	184
61	0.27000	0.27450	0.017600	176
62	0.27450	0.27900	0.018700	187
63	0.27900	0.28350	0.014800	148
64	0.28350	0.28800	0.016500	165
65	0.28800	0.29250	0.015400	154
66	0.29250	0.29700	0.016600	166
67	0.29700	0.30150	0.015400	154
68	0.30150	0.30600	0.015700	157
69	0.30600	0.31050	0.013900	139
70	0.31050	0.31500	0.014800	148

Forecast: Fluence Rate (3 ft offset) (cont'd)

Cell: G3

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
71	0.31500	0.31950	0.014900	149
72	0.31950	0.32400	0.013900	139
73	0.32400	0.32850	0.011600	116
74	0.32850	0.33300	0.009900	99
75	0.33300	0.33750	0.009700	97
76	0.33750	0.34200	0.009800	98
77	0.34200	0.34650	0.009900	99
78	0.34650	0.35100	0.008200	82
79	0.35100	0.35550	0.007800	78
80	0.35550	0.36000	0.008100	81
81	0.36000	0.36450	0.007400	74
82	0.36450	0.36900	0.006800	68
83	0.36900	0.37350	0.004800	48
84	0.37350	0.37800	0.004900	49
85	0.37800	0.38250	0.004000	40
86	0.38250	0.38700	0.003400	34
87	0.38700	0.39150	0.003300	33
88	0.39150	0.39600	0.003500	35
89	0.39600	0.40050	0.002000	20
90	0.40050	0.40500	0.001000	10
91	0.40500	0.40950	0.001600	16
92	0.40950	0.41400	0.000400	4
93	0.41400	0.41850	0.000400	4
94	0.41850	0.42300	0.000000	0
95	0.42300	0.42750	0.000000	0
96	0.42750	0.43200	0.000000	0
97	0.43200	0.43650	0.000000	0
98	0.43650	0.44100	0.000000	0
99	0.44100	0.44550	0.000000	0
100	0.44550	0.45000	0.000000	0
	0.45000	+ Infinity	0.000000	0
Total:			1.000000	10000

Cumulative:

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
	-Infinity	0.00000	0.000000	0
1	0.00000	0.00450	0.000000	0
2	0.00450	0.00900	0.000000	0
3	0.00900	0.01350	0.000000	0
4	0.01350	0.01800	0.000000	0
5	0.01800	0.02250	0.000000	0
6	0.02250	0.02700	0.000000	0

Forecast: Fluence Rate (3 ft offset) (cont'd)

Cell: G3

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
7	0.02700	0.03150	0.000000	0
8	0.03150	0.03600	0.000000	0
9	0.03600	0.04050	0.000000	0
10	0.04050	0.04500	0.000100	1
11	0.04500	0.04950	0.000200	2
12	0.04950	0.05400	0.000300	3
13	0.05400	0.05850	0.000600	6
14	0.05850	0.06300	0.001100	11
15	0.06300	0.06750	0.002500	25
16	0.06750	0.07200	0.003700	37
17	0.07200	0.07650	0.005200	52
18	0.07650	0.08100	0.006700	67
19	0.08100	0.08550	0.008800	88
20	0.08550	0.09000	0.011600	116
21	0.09000	0.09450	0.014900	149
22	0.09450	0.09900	0.018500	185
23	0.09900	0.10350	0.024100	241
24	0.10350	0.10800	0.030600	306
25	0.10800	0.11250	0.037700	377
26	0.11250	0.11700	0.044200	442
27	0.11700	0.12150	0.051400	514
28	0.12150	0.12600	0.061500	615
29	0.12600	0.13050	0.072000	720
30	0.13050	0.13500	0.083100	831
31	0.13500	0.13950	0.094700	947
32	0.13950	0.14400	0.108400	1084
33	0.14400	0.14850	0.122300	1223
34	0.14850	0.15300	0.136200	1362
35	0.15300	0.15750	0.150800	1508
36	0.15750	0.16200	0.168100	1681
37	0.16200	0.16650	0.186200	1862
38	0.16650	0.17100	0.203700	2037
39	0.17100	0.17550	0.225000	2250
40	0.17550	0.18000	0.246700	2467
41	0.18000	0.18450	0.270400	2704
42	0.18450	0.18900	0.296200	2962
43	0.18900	0.19350	0.321200	3212
44	0.19350	0.19800	0.347200	3472
45	0.19800	0.20250	0.372700	3727
46	0.20250	0.20700	0.397200	3972
47	0.20700	0.21150	0.420900	4209
48	0.21150	0.21600	0.444600	4446

Forecast: Fluence Rate (3 ft offset) (cont'd)

Cell: G3

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
49	0.21600	0.22050	0.466500	4665
50	0.22050	0.22500	0.490000	4900
51	0.22500	0.22950	0.511300	5113
52	0.22950	0.23400	0.532300	5323
53	0.23400	0.23850	0.556000	5560
54	0.23850	0.24300	0.578500	5785
55	0.24300	0.24750	0.597500	5975
56	0.24750	0.25200	0.616700	6167
57	0.25200	0.25650	0.637300	6373
58	0.25650	0.26100	0.656400	6564
59	0.26100	0.26550	0.674900	6749
60	0.26550	0.27000	0.693300	6933
61	0.27000	0.27450	0.710900	7109
62	0.27450	0.27900	0.729600	7296
63	0.27900	0.28350	0.744400	7444
64	0.28350	0.28800	0.760900	7609
65	0.28800	0.29250	0.776300	7763
66	0.29250	0.29700	0.792900	7929
67	0.29700	0.30150	0.808300	8083
68	0.30150	0.30600	0.824000	8240
69	0.30600	0.31050	0.837900	8379
70	0.31050	0.31500	0.852700	8527
71	0.31500	0.31950	0.867600	8676
72	0.31950	0.32400	0.881500	8815
73	0.32400	0.32850	0.893100	8931
74	0.32850	0.33300	0.903000	9030
75	0.33300	0.33750	0.912700	9127
76	0.33750	0.34200	0.922500	9225
77	0.34200	0.34650	0.932400	9324
78	0.34650	0.35100	0.940600	9406
79	0.35100	0.35550	0.948400	9484
80	0.35550	0.36000	0.956500	9565
81	0.36000	0.36450	0.963900	9639
82	0.36450	0.36900	0.970700	9707
83	0.36900	0.37350	0.975500	9755
84	0.37350	0.37800	0.980400	9804
85	0.37800	0.38250	0.984400	9844
86	0.38250	0.38700	0.987800	9878
87	0.38700	0.39150	0.991100	9911
88	0.39150	0.39600	0.994600	9946
89	0.39600	0.40050	0.996600	9966
90	0.40050	0.40500	0.997600	9976

Forecast: Fluence Rate (3 ft offset) (cont'd)

Cell: G3

<u>Group</u>	<u>Start Value</u>	<u>End Value</u>	<u>Prob.</u>	<u>Freq.</u>
91	0.40500	0.40950	0.999200	9992
92	0.40950	0.41400	0.999600	9996
93	0.41400	0.41850	1.000000	10000
94	0.41850	0.42300	1.000000	10000
95	0.42300	0.42750	1.000000	10000
96	0.42750	0.43200	1.000000	10000
97	0.43200	0.43650	1.000000	10000
98	0.43650	0.44100	1.000000	10000
99	0.44100	0.44550	1.000000	10000
100	0.44550	0.45000	1.000000	10000
	0.45000	+ Infinity	1.000000	10000

End of Forecast

Assumptions

Assumption: Sediment Thickness

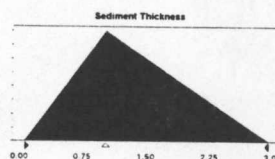
Cell: A5

Triangular distribution with parameters:

Minimum	0.00
Likeliest	1.00
Maximum	3.00

Selected range is from 0.00 to 3.00

Mean value in simulation was 1.33



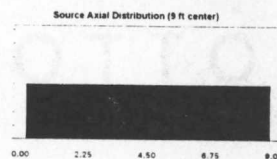
Assumption: Source Axial Distribution (9 ft center)

Cell: B1

Uniform distribution with parameters:

Minimum	0.00
Maximum	9.00

Mean value in simulation was 4.50



Assumption: Source Radial Offset

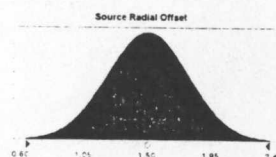
Cell: C1

Normal distribution with parameters:

Mean	1.50
Standard Dev.	0.30

Selected range is from -Infinity to +Infinity

Mean value in simulation was 1.50



Assumption: Duct Thickness

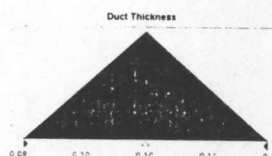
Cell: A3

Triangular distribution with parameters:

Minimum	0.09
Likeliest	0.10
Maximum	0.11

Selected range is from 0.09 to 0.11

Mean value in simulation was 0.10



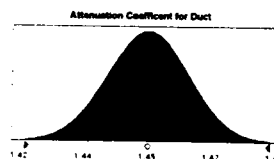
Assumption: Attenuation Coefficient for Duct

Cell: E1

Normal distribution with parameters:

Mean	1.45
Standard Dev.	0.01

Selected range is from -Infinity to +Infinity
Mean value in simulation was 1.45



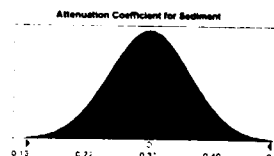
Assumption: Attenuation Coefficient for Sediment

Cell: E2

Normal distribution with parameters:

Mean	0.31
Standard Dev.	0.06

Selected range is from -Infinity to +Infinity
Mean value in simulation was 0.31



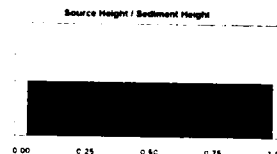
Assumption: Source Height / Sediment Height

Cell: A6

Uniform distribution with parameters:

Minimum	0.00
Maximum	1.00

Mean value in simulation was 0.50



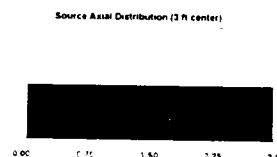
Assumption: Source Axial Distribution (3 ft center)

Cell: B3

Uniform distribution with parameters:

Minimum	0.00
Maximum	3.00

Mean value in simulation was 1.50



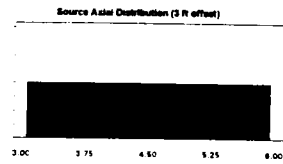
Assumption: Source Axial Distribution (3 ft offset)

Cell: B5

Uniform distribution with parameters:

Minimum	3.00
Maximum	6.00

Mean value in simulation was 4.50



End of Assumptions

VITA

Mark McHugh was born on December 13, 1965, in Chicago, IL. Despite this urban beginning, his family moved to western Kentucky in 1967. There he was reared in a small farming community and graduated from the local public high school in 1983. He attended the Virginia Military Institute (majoring in physics) for one and one half years and then Murray State University (majoring in sociology) for another one and one half years before enlisting in the U.S. Navy in 1986. He completed the course work for his B.A. in Sociology by attending night school at Rollins College in Orlando, FL while completing Naval Nuclear Power and Propulsion School in 1987.

A seven year assignment aboard the USS Enterprise allowed him the opportunity to circumnavigate the globe, with the final destination of Newport News Shipyard for the five year refueling and overhaul of the ship's eight reactor plants. It was in Newport News that he again attended night school full-time at Christopher Newport University and completed 42 hours of post-graduate work in mathematics and mechanical engineering and a B.S. in Radiation Protection in 1994. During this time he also gained extensive health physics and nuclear engineering operations experience as the ship's Health Physics Manager and a power plant shift supervisor. It was also at this time that he attained registration with the National Registry of Radiation Protection Technologists.

He is currently working his way through the University of Tennessee, Knoxville Master of Science program in Nuclear Engineering. Once again he is doing this by attending night school full-time and working full-time at ORNL's RDF on a number of different projects. He looks forward to finishing his degree in December 1995 so that he can spend more time with his family.